Near-field Heat Transfer by Standing EM Waves

Thomas Prevenslik
QED Radiations, Berlin 10777, Germany

Abstract: The history of near-field heat transfer in nanoscale gaps between macroscopic bodies is based on the Fluctuation Dissipation Theorem (FDT) that requires heat upon absorption of EM radiation to produces temperature fluctuations which means temperature fluctuations can produce EM radiation. But under EM confinement, the Planck law precludes temperature fluctuations in nanoscale gaps which heat may be conserved by creating EM radiation. However, all known near-field heat transfer theories are based on the difference of surface temperatures of nanoscale gaps. In effect, the Planck law requires theories of near-field heat transfer that do not depend on temperature. One such theory is simple QED that was formulated based on the Planck law and conserves heat by creating temperature independent EM standing waves across the nanoscale gap. Current near-field theories are discussed in relation to simple QED with applications relevant to graphene including: hyperbolic plasmons, super-Planckian radiation, and bright VIS light. The application of bright VIS emission is notable in that under electrical fields, current near-field theory claims 2000 K temperatures are produced in a graphene layer over a nanoscale trench, but bright white light requires 5000 K temperatures. Jn contrast, simple QED claims the graphene remains at ambient temperature, and instead soft X-rays are produced across the graphene thickness, the heat of which excites overtones of standing EM waves in the trench to produce bright white light. Current near-field theories are shown invalid by the Planck law while experimental data is explained by temperature independent standing EM waves consistent with simple QED.

Keywords: Near-field heat transfer, graphene, standing EM waves, Planck law, simple QED

I. INTRODUCTION

Near field heat transfer began over a decade ago with the finding the Stefan-Boltzmann law could not explain the heat flux between hot and cold bodies separated by a small gap d illustrated in Fig. 1.

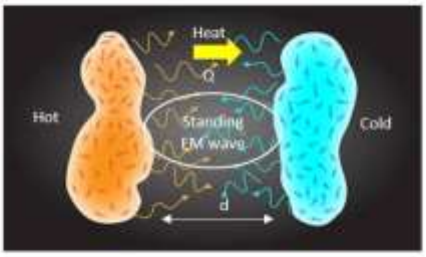

Figure 1. Near-field Heat Transfer

In the past, the mechanism by which heat Q flows from hot to cold bodies was extensively sought, all of which assumed surface temperatures of hot and cold bodies, the difficulty of measuring surface in gaps avoided by assuming bulk values. Non-thermal EM waves standing across the gap does not require surface temperatures, but presumably were excluded because temperature differences between bodies are normally necessary for heat flow, a true statement, but only for thermal heat. EM radiation standing across the gap d transferring heat Q without a temperature difference is shown in Fig. 1.

Nevertheless, all known near-field heat transfer mechanisms transfer heat Q by surface temperature. What this means is temperature dependent phonons and evanescent waves known to exist in surfaces of bodies separated by large distances are assumed to exist in nanoscale gaps. However, the Planck law [1] of quantum mechanics (QM) denies atoms in the surfaces of nanoscale gaps the heat capacity to change in temperature that is understood by considering the average Planck energy E of the atom mediated by the Bose distribution,

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

and at 300 K is plotted in relation to classical physics in Fig. 2.

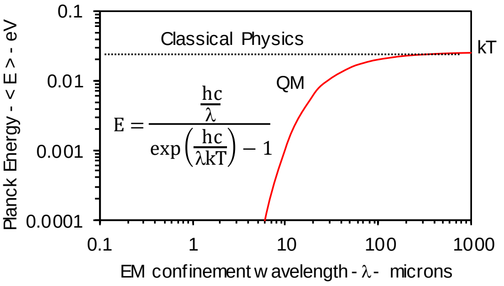

Figure. 2: Planck law of QM at 300 K
In the inset, E is Planck energy, h Planck’s constant, c light speed, k Boltzmann’s constant, T temperature, and λ the EM wavelength.

The Planck law at 300 K shows classical physics allows the atom to have constant thermal kT heat capacity over all EM wavelengths λ. QM differs as the kT heat capacity decreases for $\lambda < 200$ μm, and vanishes at the nanoscale for $\lambda < 100$ nm.

Today, near-field heat transfer faces a dilemma in that all known theories based on phonons and/or evanescent waves or variants thereof which require the atoms in the surface of nanoscale gaps to have temperature are invalid. In effect, the Planck law requires any near-field theory to be independent of temperature.

II. PURPOSE

The purpose of this paper is to propose temperature independent simple QED heat transfer [2] as the near-field theory at the nanoscale. Comparisons are made to experimental data in the literature.

III. THEORY

Simple QED is the consequence of the Planck law denying atoms in nanostructures the heat capacity to increase in temperature upon the absorption of heat. QED stands for quantum electrodynamics, a complex theory based on *virtual* photons advanced by Feynman [3] and others. Simple QED is far simpler only requiring the heat capacity of the atoms in nanostructures to vanish allowing conservation to proceed by the creation of *real* photons comprising EM waves that stand across the nanostructure.

Similar to atomic quantum states described by electrons in discrete orbitals, simple QED quantum states are dependent on the dimension of the nanostructure over which the EM waves stand. The Planck energy E of a simple QED photon standing across a distance d is given by the time τ for light to travel across and back, $\tau = 2d/(c/n)$, where n is the index of refraction of the nanostructure material. Hence, the Planck energy E of the simple QED photons is, $E \sim h/\tau$ having wavelength $\lambda = 2nd$,

$$E = \frac{hc}{2nd} \tag{2}$$

To illustrate simple QED, consider heat flux Q having wavelength λ_o heating a nanoparticle (NP) of diameter d. For $\lambda_o >> d$, the NP is immersed in the heat flux Q as illustrated in Fig. 3.

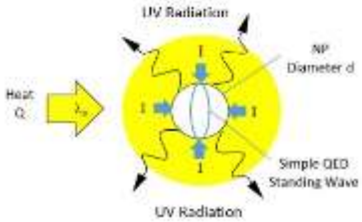

Figure 3. Laser Heating of a NP

Importantly, heat flux Q absorbed by the NP must be placed under brief EM confinement to produce the standing simple QED photons. The EM is not produced by some structuring of the NP surface, but rather produced by the heat Q flux itself.

EM confinement is the consequence of the Planck law denying NP atoms the heat capacity to allow the temperature changes required for Fourier heat conduction, and therefore the heat flux Q cannot penetrate the NP surface. Indeed, the simple QED photon is created by a non-thermal EM standing wave under EM confinement to allow transit across and back the NP diameter d in time $\tau = 2nd/c$.

The EM confinement at the NP surface is caused by the brief inward spherical Poynting vector S = Q carrying momentum I shown as blue arrows in Fig. 3. Here, U is the energy from the heat flux Q acting over an increment of time Δt, $U = QA \cdot \Delta t$, where A is the NP surface area, units of S and Q ~ Wm^{-2} and U ~ J giving momentum $I = U/c \sim Nt \cdot s$. Over time Δt, N simple QED photons having momentum $I_P = h/2nd$ are created, where $N < I/I_P$. Once $NI_P > I$, the simple QED photons are emitted to surroundings.

In interest of whether simple QED photons may be created from the thermal surroundings alone, consider a NP in the ambient environment at temperature T. The Planck law gives the heat flux Q_T as radiant thermal power energy density,

$$Q_T = \left(\frac{2c}{\lambda^4}\right) \frac{\frac{hc}{\lambda}}{\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]} \tag{3}$$

The number N_T of simple QED photons created from the ambient at temperature T is $N_T = U_T V/E$, where $U_T = Q_T \cdot \Delta t$, V volume, and $E = hc/2nd$. The momentum $I_T = U_T/c$ and $I_P = N_T\ h/2nd$. The importance of the Planck law in denying NP temperature fluctuations means Brownian motion ceases. In effect, the thermal heat flux Q_T produces momentum I_T because of the temperature gradient with the NP surface at absolute zero.

The EM confinement of simple QED photons in the NP by the inward spherical momentum is not applicable to near-field heat transfer in gaps between hot and cold bodies. Unlike phonons [4,5] in nanoscale gaps, simple QED in gaps is shown Fig. 4.

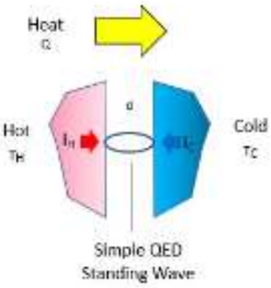

Figure 4. Near-field Heat Transfer.

Fig. 4 shows heat Q transferred from hot to cold bodies across a nanoscale gap with vanishing thermal kT energy of atoms in hot and cold surfaces as required by the Planck law. To compensate for the surface atoms effectively at absolute zero, the number of atoms in hot N_H and cold N_C bodies having thermal kT energy $U_H = \frac{3}{2} \cdot N_H \, kT_H$ and $U_C = \frac{3}{2} \cdot N_C \cdot kT_C$ form Poynting vectors of momentum $I_H = U_H/c$ and $I_C = U_C/c$ directed toward the respective gap surfaces provide the EM confinement to create the simple QED photons.

Heat Q flows if the momentum $I_H > I_C$. In the gap, the Planck law precludes conservation of Q by a change in temperature, and instead proceeds by the creation of simple QED radiation in the form of non-thermal EM standing waves.

Importantly, the EM standing waves are non-thermal. The Planck law temperature dependence is given by,

$$E_H = (hc/2d) \cdot [\exp(hc/2dkT_H) - 1]^{-1} \qquad (4)$$
$$E_C = (hc/2d) \cdot [\exp(hc/2dkT_C) - 1]^{-1}$$

At 300 K, Fig. 1 shows E_H and E_C cannot exist thermally for $d = \lambda/2 < 4$ μm which is precisely why simple QED requires non-thermal EM standing waves.

IV. APPLICATIONS

A. Hyperbolic Plasmons

In 2015, heat flux Q in near-field heat transfer [6] by excitation of surface plasmons in graphene ribbons was proposed and very recently [7] to enable the enhancement of thermal radiation across gaps far beyond Planck's blackbody limit.

The near-field enhancement is based on broadband singularities of density of states caused by hyperbolic plasmons in combination with evanescent waves in gap surfaces having finite and different temperatures. Heat flux Q across a pattern of ribbons in single layers of graphene sheet with hot T_2 and cold T_1 surface temperatures is illustrated in Fig. 5.

Figure 5. Near-field heat transfer - Graphene Ribbons

The near field enhancement [6,7] is consistent with the fluctuation-dissipation theorem (FDT) that states:

> "EM radiation causing thermal fluctuations
> implies thermal fluctuations produce EM radiation"

Hence, the FDT is not applicable when EM radiation is absorbed in nanoscale gaps without causing temperature fluctuations.

Indeed, simple QED based on the Planck law is not consistent with the FDT at the nanoscale by requiring heat to be conserved by EM radiation without thermal fluctuations, but EM radiation cannot produce heat without thermal fluctuations. What this means is the FDT is a classical notion not applicable to the nanoscale.

Nevertheless, near-field heat transfer [6,7] based on the FDT gives the heat flux Q is,

$$Q = \int_0^{\infty} (\Theta[\omega, T_2]) - \Theta(\omega, T_1)) d\omega \bullet \qquad (5)$$
$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{\xi(\omega, k_x, k_y)}{8\pi^3} dk_x dk_y$$

where, $\Theta(\omega,T_2)$ and $\Theta(\omega,T_1)$ are the average Planck energy E of the atom in Eqn. 1 expressed in frequency $\omega = c/2\pi\lambda$ with T_2 and T_1 being the hot and cold temperatures of the graphene ribbons shown in Fig. 5.

In near-field heat transfer the heat flux Q across nanoscale gaps has not been confirmed by experiment to establish whether a temperature difference for hyperbolic plasmons even exists. Currently, hyperbolic plasmons are shown [8] to exist on the free surface of thin films of WTe2 over a range of 16 to 23 microns at 10 K. But whether hyperbolic plasmons enhance the heat flux Q across nanoscale gaps is yet to be demonstrated.

Perhaps, experimental verification is not necessary as the Planck law requires near-field heat flux Q to vanish as $T_1 = T_2$ in Eqn. 5 making moot the existence of hyperbolic plasmons in nanoscale gaps.

B. Super-Planckian Radiation

Graphene sheets of single atom monolayers is thought [9] to perform an important role in near-field heat transfer because of strong IR plasmonic response. Phonon tunneling is thought to replace thermal radiation, but EM waves standing across the gaps is contrarily reported. Nevertheless, the FDT basis to the Thermal Fluctuating Electrodynamic (TFE) theory is thought to characterize near-field heat transfer.

The TFE theory is similar to the near-field theory discussed for hyperbolic plasmons [6,7] in nanoscale vacuum gaps shown to have vanishing heat flux Q as the gap surface temperatures $T_1 = T_2$ as required by the Planck law. Similarly, the TFE theory applied to plasmons in graphene having nanoscale gaps [9] cannot be the source of heat flux Q.

With regard to larger gap sizes, Fig. 1 depicting the Planck law at 300 K shows the Planck energy E at 8 μm does not vanish, but is 0.0001 eV or about 3 orders of magnitude < kT that also precludes temperature fluctuations. This means the maximum allowable gap $d < \lambda/2 = 4$ μm. Therefore, the gaps studied [9] with d = 0.43, 1.6, and 3.7 μm produce EM radiation in the near IR at 0.83, 3.2, and 7.4 μm consistent with simple QED, but otherwise do not validate TFE theory.

Since EM waves are central to simple QED based on Planck's law, the standing waves measured [9] in the vacuum gaps include many higher frequency overtones of the fundamental as shown in Fig. 6.

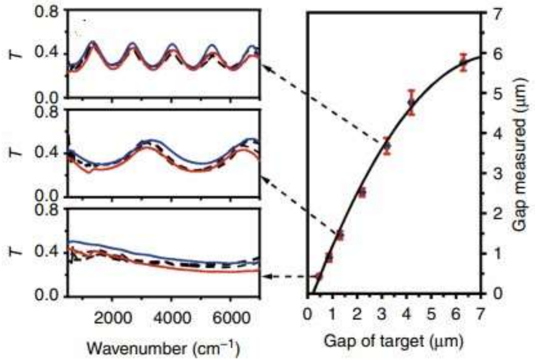

Figure 6. EM Wave Overtones

In Fig. 6, the gap d is shown on the right and overtones in the transmission T on the left. The EM standing wavelengths $\lambda = 2d/N$, where N = 1,2,3,... The overtones vary harmonically with wavelength λ expressed in wavenumber from 800 to 7000 cm^{-1}. The harmonic amplitudes are anti-nodes between nodes of zero amplitude. The overtone modes for gaps 0.43, 1.6, and 3.7 μm are shown in Fig. 7.

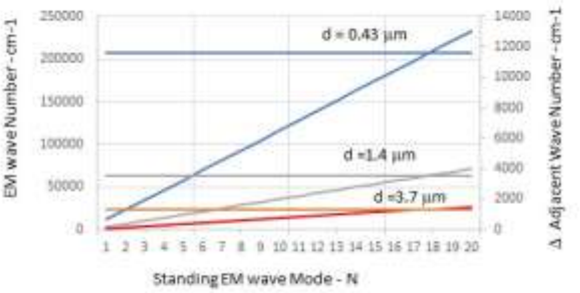

Figure 7. Standing EM Wave Overtones

The EM wave for d = 0.43 μm (blue) corresponds to wave numbers 12,000 to 232,000 cm^{-1} (left) ordinate for modes N = 1 and 20, respectively. The wave number between adjacent nodes given on the (right) ordinate is the same 12,000 cm^{-1} for all modes. Fig. 6 left-bottom shows half-wave of ~ 6000 cm^{-1}.

A better comparison is made for d = 3.7 μm (red) corresponding to wave numbers 1350 to 27,000 cm^{-1} at modes 1 and 20 having adjacent nodes spaced at 1350 cm^{-1}. Fig. 6 left-top shows peak-to-peak wave numbers ~ 1500 cm^{-1} which is reasonably correct.

The TFE theory based on phonon tunneling across the gap cannot like other near-field theories be valid because different surface temperatures are required which is contrary to the Planck law. But the data [9] is consistent with the temperature independent EM standing waves in simple QED.

C. Bright VIS Light

Bright emission in the visible range reported [10] from electrically biased suspended graphene layers is thought caused by hot electrons (~2,800 K) resulting in a 1,000-fold enhancement in thermal radiation efficiency, the emission mediated by distance d of the layer to the substrate as shown in Fig. 8.

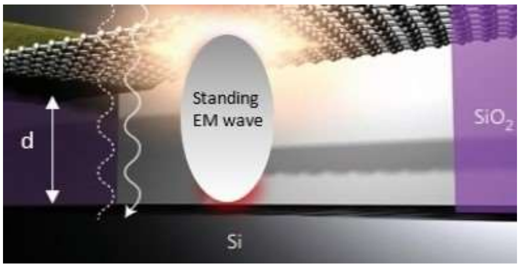

Figure 8. Bright Graphene Emission

The VIS emission is observed as the voltage reaches a threshold of ~ 0.4 V μm^{-1}. Fig. 8 shows the graphene layer is suspended a distance d over a submicron trench. Lattice temperatures of 1800 K are thought to be localized at the center of the graphene layer to significantly enhance the thermal light emission. The light emission is shown to include reflected light from the trench suggesting standing EM waves are produced.

Indeed, observations [10] show overtones of the fundamental EM wave standing between the graphene layer and the trench that was related to the change in Planck energy ΔE between two consecutive interferences,

$$\Delta E = \frac{1239.8\ \mathrm{nm}}{2d}\,\mathrm{eV} \qquad (6)$$

In the manner of EM standing waves, the Planck energy ΔE was found insensitive to the number of graphene layers and not affected by the absorption and reflection of the graphene layers.

The source of EM energy [10] creating the standing EM waves in air or vacuum is the Joule heating that produces temperatures T ~ 2000 K in the graphene layers. The classical Fourier diffusive equation was assumed,

$$\frac{d^2T}{dx^2} + \frac{P}{\kappa WtL} - \frac{2g}{\kappa t}(T - T_o) = 0 \qquad (7)$$

where, κ is the thermal conductivity and t = 0.34 nm is the thickness of graphene, and $g = 2.9 \times 10^4\ \mathrm{W\ m^{-2}\ K^{-1}}$ is the thermal conductance per unit area between graphene and air. In a vacuum, g = 0.

Simple QED differs significantly from classical Fourier thermal diffusion as the graphene atoms have vanishing heat capacity across the thickness t of the graphene layer that not only precludes temperatures of 2000 K, but requires no change in temperature.

Instead, EM radiation is produced from the Planck energy E of simple QED radiation standing across the layer thickness, E = hc/2nd. Since the refractive index n of graphite from 50 - 1000 eV is n ~ 1, the single atom graphene thickness d = t = 0.337 nm gives wavelength 2nd = 0.674 nm and E = 1.8 keV, but fluoresces down to ~ 270 eV soft X-rays. Taking graphite as representative of graphene, the CK bands [12] are shown in Fig. 9.

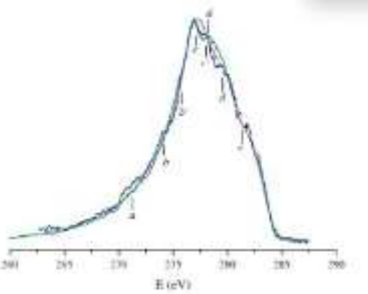

Figure 9. Soft X-ray Absorption of Graphite

However, it is unlikely soft X-rays can fluoresce down to visible light levels. Instead, simple QED conserves the soft X-ray heat in the trench by creating standing EM waves that then produce overtones observed as bright VIS emission

Otherwise, simple QED is consistent with [10] in the interpretation of the overtones of EM waves standing in the trench. Indeed, Fig. 10 shows the change in Planck energy ΔE between adjacent overtone modes has fundamental wavelength λ = 2d giving ΔE = hc/2d identical to Eqn. 6.

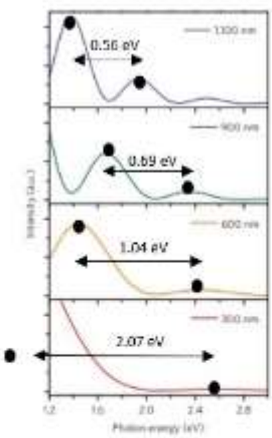

Figure 10. Standing EM Wave Overtones

V. CONCLUSIONS

The FDT assumes since EM radiation produces heat with temperature fluctuations then temperature fluctuations can produce EM radiation.

But the Planck law precludes heat from EM radiation creating temperature fluctuations in nanoscale gaps which means the FDT is not applicable and heat may only create EM radiation at the nanoscale.

All known near-field heat transfer theories assume temperature fluctuations in gaps and implicitly require temperature differences between gap surfaces are invalid by the Planck law.

Only temperature independent near-field theories are valid at the nanoscale, one proposal of which is simple QED based on the Planck law itself.

Hyperbolic phonons and evanescent waves valid on the surface of macroscopic bodies do not exist in the surfaces of nanoscale gaps.

Electric field induced 2000 K temperatures do not exist in suspended single atom graphene layers. Instead, Joule heat is conserved by creating soft X-rays across the layer thickness, the heat of which is then conserved by creating the fundamental of EM waves standing between the graphene layer and the bottom of the trench. The white light is a mix of the higher VIS overtones of the fundamental EM standing wave.

REFERENCES

[1] Planck M. [1900] On the Theory of the Energy Distribution Law of the Normal Spectrum. Verhandl. Dtsch. Phys. Ges., 2:2-37.
[2] Prevenslik T. Simple QED Theory and Applications. nanoqed.org, 2015-2020.
[3] Feynman R., QED: The Strange Theory of Light and Matter. Princeton University Press, 1976.
[4] Prevenslik T. [2021] Phonons leap across a nanoscale gap? See nanoqed.org, 2021.
[5] Fong K. Y., et al. 2019. Phonon heat transfer across a vacuum through quantum fluctuations. Nature, 576:243-248.
[6] Liu X. L., Zhang Z. M. [2015] Giant enhancement of nanoscale thermal radiation based on hyperbolic graphene plasmons. Appl. Phys. Lett. 107:143114.
[7] Zhou C. L., et al. [2020] Near-field electromagnetic heat transfer through nonreciprocal hyperbolic graphene plasmons Nanoscale And Microscale Thermophysical Engineering 24:168–183.
[8] Wang C. et al. [2020] Van der Waals thin films of WTe2 for natural hyperbolic plasmonic surfaces. 11:1158.
[9] Yang J., et al. [2018] Observing of the super-Planckian near-field thermal radiation between graphene sheets. Nature Communications. 9:4033.
[10] Kim Y. D., et al. [2015] Bright visible light emission from graphene. Nature Nanotechnology 10:676–681.
[11] Dorgan V. E., et al. [2013] High-Field Electrical and Thermal Transport in Suspended Graphene. Nano Lett. 13:4581–4586.
[12] Ilkiv B., et al. [2012] X-Ray Emission Spectra of Graphene Nanosheets. Journal of Nanoscience and Nanotechnology 12:8913-9.