White Light from Graphene by Quantum Mechanics

Thomas Prevenslik
QED Radiations, Berlin 10777, Germany

Abstract: Near-field heat transfer in nanoscale gaps assumes the atom has kT heat capacity in stark contrast to the Planck law of quantum mechanics (QM) that requires temperature fluctuations to vanish. Since all known near-field theories assume temperature fluctuations, no valid near-field theories may be said to exist today. The Planck law shows the heat capacity of a body depends on the EM confinement wavelength of the constituent atoms given by the EM wave standing or travelling across the body. Classical physics based on macroscopic bodies with long wavelengths allows the atom upon absorbing heat to increase in temperature. However, the Planck law applied to nanoscopic bodies having submicron wavelengths differs significantly from classical physics by denying the constituent atoms the heat capacity to increase in temperature. In this paper, the difference between classical physics and the Planck law is illustrated for Joule heated white light (WL) emission from a single atom graphene layer at ambient temperature suspended over a nanoscale trench. Classical physics based on the Fourier law gives temperatures of about 1800 K, but WL is usually thought to occur at temperatures as high as 5000 K. However, high temperatures are questionable as WL is observed in graphene layers at 10 K. In this regard, the theory of simple QED nanoscale heat transfer based on the Planck law claims the single layer graphene remains at ambient temperature by emitting soft X-rays that heat the trench. But like the graphene layer, the nanoscale trench also cannot increase in temperature, and instead simple QED creates standing IR waves, the VIS overtones of which produce the WL.

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

I. INTRODUCTION

Simple QED heat transfer evolved a decade ago from the observation [1] that near-field theories [2-4] based on classical heat Q flow by temperature fluctuations show the Stefan-Boltzmann is not applicable to nanoscale gaps. Nevertheless, all known near-field theories were inconsistent with the Planck law [5] that denies the atom the heat capacity to conserve heat at the nanoscale and instead allowed temperature fluctuations to exist in nanoscale gaps.

Instead of temperature dependent near-field theories, simple QED finds consistency with the Planck law by conserving heat Q by non-thermal EM waves as depicted in Fig. 1.

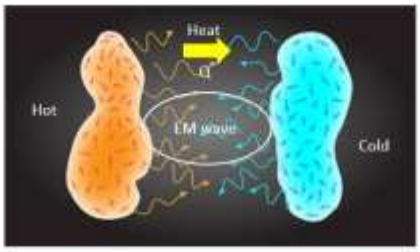

Figure 1. Simple QED heat transfer

Unlike simple QED, near-field theories that require gap surface temperatures are unverifiable because of the difficulty in measuring surface temperatures in nanoscale gaps, and therefore are forever questionable.

Nevertheless, all known near-field theories transfer heat Q by differences in surface temperature, and therefore all are questionable. Simple QED based on the Planck law avoids the problem of unverifiable surface temperatures by denying atoms in the surfaces of nanoscale gaps the heat capacity to change in temperature. Consider the average Planck energy E of the atom mediated by the Bose distribution,

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

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

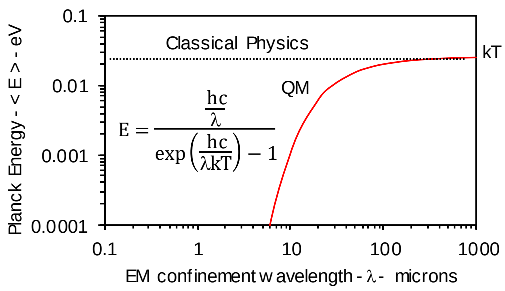

Figure. 2: Planck law of QM at 300 K
In the inset, E is Planck energy, h Planck's constant, c light speed, k Boltzmann's constant, T temperature, and λ the EM wavelength.

Fig. 2 shows the Planck law at 300 K follows classical physics allowing the atom to have kT heat capacity and change temperature for all EM wavelengths λ > 200 μm. But for λ < 200 μm, the Planck law differs as the kT heat capacity dramatically decreases, e.g., a nanoparticle (NP) having heat capacity E = 100 μeV at λ ~ 6 μm has heat capacity over 2 orders of magnitude lower than at E = 0.0254 eV where temperature changes occur upon absorbing heat. At λ = 4 μm, E = 1 μeV the kT heat capacity is lowered over 4 orders of magnitude. In the near-field for λ < 100 nm, the kT heat capacity vanishes.

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 fluctuations are therefore 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 as the near-field theory at the nanoscale. Comparisons are made to experimental data on WL 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 [6] 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 form across the nanostructure.

Similar to atomic quantum states described by electrons in discrete orbitals, simple QED quantum states are dependent on the dimension d of the nanostructure over which the EM waves form. The Planck energy E of a simple QED wave travelling across a distance d of a nanostructure 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 material. Hence, the Planck energy E of the simple QED photons is, E ~ h/τ having wavelength $\lambda = 2nd$,

$$E = \frac{hc}{2nd} \qquad (2)$$

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

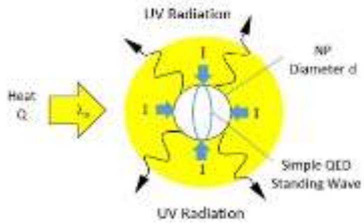

Figure 3. Heating of a NP

Importantly, heat flux Q absorbed by the NP must be placed under brief EM confinement to produce the standing simple QED waves. The EM confinement 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 kT heat capacity to allow the temperature changes to conserve heat Q by Fourier diffusion. Hence, the heat Q cannot penetrate the NP surface, the momentum I of which providing the EM confinement. Indeed, heat Q may only be conserved by an EM wave transiting across and back the NP diameter d in the time τ = 2nd/c giving the Planck energy E of the wave, E = h/τ = hc/2nd.

The EM confinement at the NP surface is the brief inward spherical 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, the units of S and Q ~ Wm^{-2} and U ~ J giving momentum I = U/c ~ Nt·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 waves are emitted to surroundings.

Of interest is 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,

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

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 the NP. 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 waves in the NP by the inward spherical momentum is not applicable to near-field heat transfer in gaps between hot and cold bodies is shown Fig. 4.

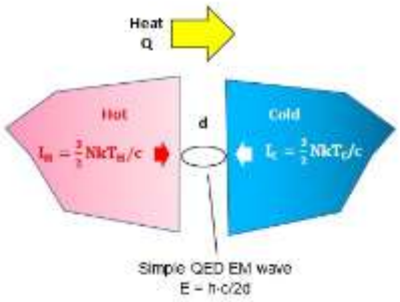

Figure 4. Near-field Heat Transfer.

Unlike the NP having simple QED standing waves before emission, the simple QED waves in the near-field are not standing, but travelling during transfer of heat Q across the nanoscale gap between hot and cold bodies. What this means is in the near-field, the gap continuously forms propagating EM waves from heat energy Q having wavelength $\lambda = 2d$.

The EM confinement of heat Q flux is the momenta I_H and I_C of the thermal kT energy of atoms in hot and cold bodies at temperatures T_H and T_C. The momenta are directed by the temperature gradient toward the respective gap surfaces at absolute zero induced by the Planck law. Hence, an arbitrary number N of atoms in hot and cold bodies having kT energy $U_H = \frac{3}{2} \cdot N\, kT_H$ and $U_C = \frac{3}{2} \cdot N \cdot kT_C$ form the momenta $I_H = U_H/c$ and $I_C = U_C/c$ directed toward the respective gap surfaces at absolute zero, the momenta I_H, I_C providing the EM confinement to form the propagating simple QED waves transferring Q across the gap

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

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

At 300 K, Fig. 2 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 waves.

IV. APPLICATIONS

Bright WL emission in the visible range reported from electrically biased suspended graphene layers is thought [7] caused by hot electrons (~2,800 K) resulting in a 1,000-fold enhancement in thermal radiation efficiency, the emission mediated by distance d from the graphene layer of the layer to the trench bottom as illustrated in Fig. 5.

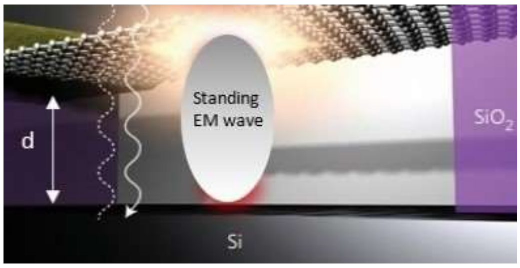

Figure 5. Graphene WL Emission

The WL emission is observed as the voltage reaches a threshold of ~ 0.4 V μm^{-1}. Fig. 5 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 [7] 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,

$$\Delta E = \frac{1239.8 \text{ nm}}{2d} \text{eV} \quad (5)$$

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 [8] creating the EM waves in air or vacuum is the Joule heating that is thought to produce temperatures T ~ 2800 K in the graphene layers. The classical Fourier diffusive equation was assumed,

$$\frac{d^2T}{dx^2} + \frac{P}{\kappa W t L} - \frac{2g}{\kappa t}(T - T_o) = 0 \quad (6)$$

where, κ is the thermal conductivity and t = 0.34 nm is the thickness of graphene, and $g = 2.9 \times 10^4$ 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 kT heat capacity across the thickness t of the graphene layer that not only precludes temperatures of 2800 K, but requires the layer to remain at ambient temperature.

The Planck energy E of simple QED waves travelling across the layer thickness d, E = hc/2nd. Since the refractive index n of graphite from soft x-rays 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 [9] are shown in Fig. 6.

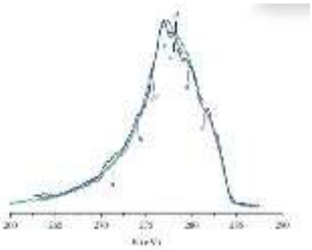

Figure 6. Soft X-ray Absorption of Graphite

However, it is unlikely 270 eV soft X-rays fluoresce down to VIS light levels. Instead, simple QED conserves the soft X-ray heat in the trench by creating standing EM waves that then produce the overtones observed as bright VIS emission

Otherwise, simple QED is consistent with [7] in the interpretation of the overtones of EM waves standing in the trench. Indeed, Fig. 7 shows the change in Planck energy ΔE between adjacent overtone modes has fundamental wavelength $\lambda = 2d$ giving $\Delta E = hc/2d$ identical to Eqn. 5.

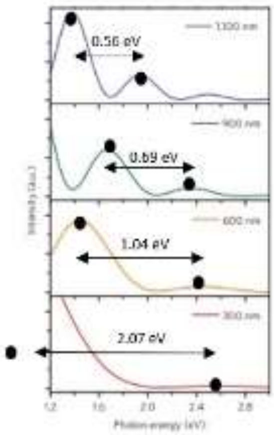

Figure 7. Standing EM Wave Overtones

The important result is simple QED predicts WL is created at ambient temperature and not at Joule heated electron temperatures of 2800 K. Indeed, no dependence of WL emission intensity [10] with sample temperature was observed even at cryogenic 10 K. Fig. 8 shows WL intensity by QM far exceeds BB radiation at 4315 K shown in Fig. 8.

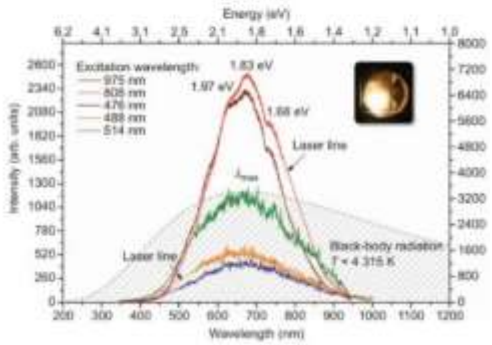

Figure 8. WL emission at 10 K

V. CONCLUSIONS

Near-field heat transfer assumes heat produces temperature fluctuations in nanoscale gaps which is refuted by the Planck law that denies atoms in gap surfaces the kT heat capacity to conserve heat by temperature fluctuations.

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

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

Electric field induced 2800 K temperatures do not exist in suspended single atom graphene layers.

Simple QED conserves Joule heat by creating 1.8 keV soft X-rays across the 0.337 nm graphene layer thickness that fluoresce down to ~ 270 eV.

Like the graphene layer, the nanoscale trench cannot conserve the soft x-ray heat by an increase in temperature, and instead creates the IR waves standing between the graphene layer and the trench bottom.

The WL is a mix of the higher overtones of the fundamental IR standing wave.

REFERENCES

[1] Prevenslik T. Simple QED Theory and Applications. nanoqed.org, 2010-2021.
[2] Mulet, J. P., et al., [2002] Enhanced radiative heat transfer at nanometric distances. Microscale Thermophysical Engineering 6:209-222.
[3] Joulain, K., et al. [2005] Surface electromagnetic waves thermally excited: Radiative heat transfer, coherence properties and Casimir forces revisited in the near field. Surface Science Reports, 57: 59-112.
[4] Shen S., et al. [2009] Surface phonon polaritons mediated energy transfer between nanoscale gaps. Nano Letters. 9:2909-2913.
[5] Planck M. [1900] On the Theory of the Energy Distribution Law of the Normal Spectrum. Verhandl. Dtsch. Phys. Ges., 2:2-37.
[6] Feynman R., QED: The Strange Theory of Light and Matter. Princeton University Press, 1976.
[7] Kim Y. D., et al. [2015] Bright visible light emission from graphene. Nature Nanotechnology 10:676–681.
[8] Dorgan V. E., et al. [2013] High-Field Electrical and Thermal Transport in Suspended Graphene. Nano Lett. 13:4581–4586.
[9] Ilkiv B., et al. [2012] X-Ray Emission Spectra of Graphene Nanosheets. Journal of Nanoscience and Nanotechnology 12:8913-9.
[10] Strek W., et al. [2015] Laser-induced white-light emission from graphene ceramics–opening a band gap in graphene. Light: Science & Applications doi:10.1038/lsa.2015.10.