Near Field Heat Transfer in Graphene Bilayers

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Abstract: Near-field heat transfer assumes that since EM radiation upon absorption in a body produces temperature fluctuations then temperature fluctuations produce EM radiation, as heat alone producing EM radiation without temperature fluctuations is excluded. Contrarily, the Planck law precludes heat from producing temperature fluctuations in nanoscale gaps and surfaces. However, all known near-field theories are based on the unverifiable assumption that bulk temperatures exist at gap surfaces. In effect, the Planck law requires theories of near-field heat transfer that do not depend on gap surface temperatures, one such theory described herein is simple QED that conserves heat across gaps by EM waves. Current twisted bi-layer graphene (tBLG) theories based on temperature fluctuations report the heat transferred is 5 orders of magnitude higher than the blackbody (BB) limit for twist angles of only a few degrees. In contrast, simple QED shows heat is conserved across nanoscale gaps and comparison with the BB limit is meaningless, i.e., adding a nanoscale gap to a 1-D rod does not increase the heat flow along its length. The validity of simple QED depending on the EM confinement wavelength of the atom based on the Planck law is supported at cryogenic temperatures well known to shift the Planck law to long wavelengths allowing the near-field at the nanoscale at 300 K to be extended to the macroscale in 50-micron gaps at 15 K. Importantly, heat flow in nanoscale gaps above the BB limit does not mean actual heat flow is enhanced, but rather only heat flow is conserved across the gap by EM waves - not temperatures. Since all near-field theories based on temperature fluctuations in nanoscale gaps are invalid by the Planck law, future near-field research should be directed to temperature independent theories.

Keywords: Near-field heat transfer, tBLG, twisted graphene, cryogenic, Planck law, simple QED

I. INTRODUCTION

Historically, the near-field radiative heat transfer between closely spaced bodies evolved over the past decades was essentially thought [1-4] mediated by the tunneling of evanescent waves.

Today, evanescent waves [5] in the study of thermal radiation between tBLG layers is shown to give a 10-fold increase in heat flow Q over only a few degrees of twist θ as illustrated in Fig. 1.

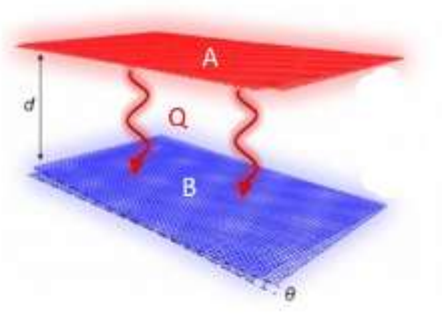

Figure 1. tBLG twist θ enhancement of heat flow Q

In Fig. 1, the heat Q flows from the hot to cold layers, the hot layer above the cold layer below designated as A and B, respectively. During twist, A and B layers remain parallel and the gap d is the same everywhere. The twist angle θ is shown in B as an in-plane rotation relative to A.

Indeed, the 10-fold increase in Q for a small twist angle is surprising as the gap d is not changed. If anything, a fraction of the B area is removed from A heat flux suggesting Q should slightly decrease - not increased 10-fold. Setting this aside, Moire' fringe patterns of tBLG are expected for twist and, indeed are well known [6] as shown in Fig. 2.

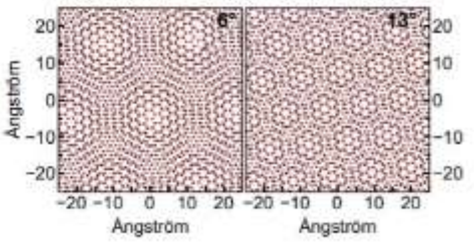

Figure 2. tBLG Moire' fringes

However, heat transfer Q is unlikely to have anything to do with Moire' fringes between A and B layers as the twist θ and not the gap d mediates the Moire' fringes. Nevertheless, tBLG is shown [5] to achieve peak heat flow at specific twist angles θ proportional to the chemical potential. Indeed, surface plasmons in tBLG are proposed to mediate radiative heat flow. Regardless, the major challenge [6] in the development of tBLG is how to implement and control the twist angle θ .

II. BACKGROUND

In the past, near-field heat transfer mechanisms by which heat Q flows from hot to cold bodies were extensively sought, all of which assumed surface temperatures of hot and cold bodies, the difficulty of measuring surface temperature in gaps avoided by assuming bulk values. Non-thermal EM waves across nanoscale gaps avoids surface temperatures. Since Fourier, only temperature differences were necessary to describe heat flow between bodies at the macroscale. But heat flow in the near-field at nanoscale gaps differs.

Today, all known near-field heat transfer mechanisms transfer heat Q by surface temperature. What this means is temperature dependent phonons, plasmons, and evanescent waves known to exist in surfaces of bodies separated by large gaps are also assumed to exist in nanoscale gaps.

However, the Planck law [7] of quantum mechanics (QM) denies atoms in the surfaces of nanoscale gaps the heat capacity to change in temperature that may be understood by considering the average Planck energy E of the atom mediated by the Bose distribution,

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

and at 300 K is plotted in relation to classical physics in Fig. 3.

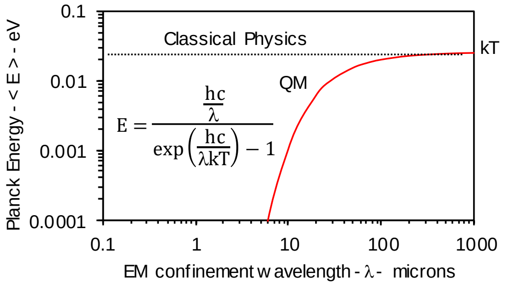

Figure. 3. Planck law of QM at 300 K
In the inset, E is Planck energy, h Planck's constant, c light speed, k Boltzmann's constant, T temperature, and λ the EM wavelength.

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 $\lambda < 0.1$ μm.

Today, near-field heat transfer faces a dilemma in that all known theories based on phonons, plasmons, and 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.

III. PURPOSE

The purpose of this paper is to propose temperature independent simple QED heat transfer [8] as the near-field theory for tBLG. Comparisons are made to experimental data in the literature.

IV. 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 [9] 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 across the nano gap or structure.

Similar to atomic quantum states described by electrons in discrete orbitals, simple QED quantum states are dependent on the dimension of the nano gap or structure over which the EM waves form. The Planck energy E of a simple QED photon 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, $E \sim h/\tau$ giving the wavelength $\lambda = 2nd$,

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

To illustrate simple QED, consider the flux Q of light or heat having wavelength λ_o interacting with a nanoparticle (NP) of diameter d. Unlike Mie theory that restricts $\lambda_o < d$ and allows Q to pass through the NP without a change in frequency, simple QED requires $\lambda_o >> d$ allowing Q to immerse the NP and provide the surrounding EM confinement to change the frequency of Q as shown in Fig. 4.

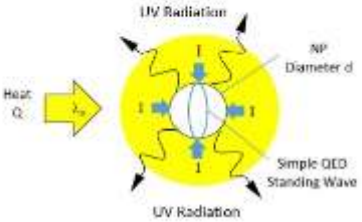

Figure 4. Heating of a NP

Importantly, frequency of Q may only change if placed under brief EM confinement to produce the simple QED photons depending on the NP diameter d. Of note, the EM confinement is not produced by some structuring of the NP surface, but rather is proposed 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 Q cannot penetrate the NP surface. Instead, the simple QED photon is created by a non-thermal EM wave that under confinement in the time $\tau = 2nd/c$ to allow transit across and back the NP diameter.

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. 4. Here, U is the energy from the heat flux Q acting over time increment Δt, $U = QA \cdot \Delta t$, where A is the NP surface area. $Q \sim Wm^{-2}$ and $U \sim J$ gives momentum $I = U/c \sim Nt \cdot s$. In time Δt, N simple QED photons are created having momentum $I_P = N \cdot h/2nd$, where $N < I/I_P$. Once $N \cdot I_P > I$, the simple QED photons are emitted to surroundings.

Whether simple QED photons may be created without an external flux Q, 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,

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

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

However, 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. Simple QED applied to near-field heat transfer across gaps is shown in Fig. 5.

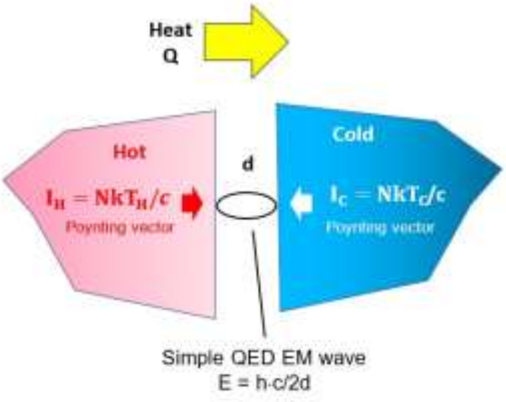

Figure 5. Near-field heat transfer in gaps

For nanoscale gaps, the thermal kT energy of atoms in hot and cold surfaces vanishes by the Planck law meaning Brownian motion ceases and surface temperatures may be considered at absolute zero. To compensate for the surface atoms, the number of atoms in hot N_H and cold N_C bodies having kT energy $U_H = \cdot 3/2\ N_H kT_H$ and $U_C = 3/2 \cdot N_C \cdot kT_C$ form Poynting vectors of momentum $I_H = U_H/c$ and $I_C = U_C/c$ directed toward the respective gap surfaces at absolute zero.

The EM confinement of the simple QED photon is provided by the inwardly disposed I_H, I_C momenta that create the non-thermal EM wave. Heat Q flows if the momenta $I_H > I_C$.

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

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

At 300 K, Fig. 3 shows E_H and E_C cannot exist thermally for $d = \lambda/2 < 4\ \mu m$ which is precisely why simple QED requires non-thermal EM waves.

IV. APPLICATIONS

Heat transfer by non-thermal simple QED induced EM waves differs from near-field theories [1-5] based on differences between surface temperatures. EM waves between twisted A and B surfaces is illustrated in Fig. 6.

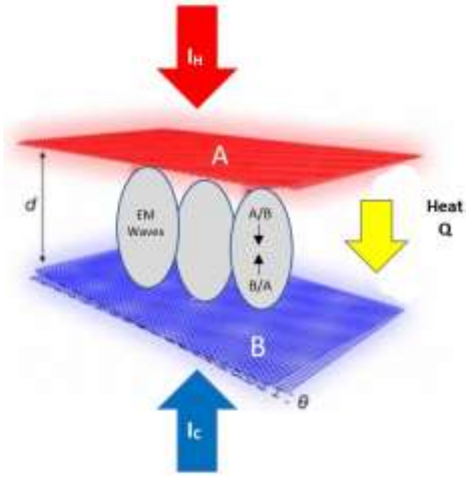

Figure 6. Simple QED - tBLG

Fig. 6 shows heat Q transfer by momenta $I_H > I_C$ of Poynting vectors conserved by the momentum of EM waves across the gap. In NPs, the spherical inward momenta briefly produce standing EM waves that then are emitted to the surroundings. The near-field differs as standing EM waves alone cannot transfer heat Q across the gap. Indeed, transverse wave motion in strings shows only a small fraction [10] is converted to longitudinal momentum thereby denying heat Q transfer by standing EM waves.

In the near-field, heat Q is transferred by the momenta I_H, I_C of 2 opposing EM waves: If Q > 0, heat flows as $I_H > I_C$ and one wave transfers hot I_H momenta A/B from A to B while the other transfers cold I_C momenta B/A from B to A. Only if Q = 0, no heat flows as $I_H = I_C$ giving the standing EM wave absent heat transfer and longitudinal momentum.

In tBLG, the heat Q transfer across gap d is based on N simple QED induced photons, and E = hc/2d is the simple QED energy. The total U energy is,

$$U = N\frac{hc}{2d}$$

where, U ~ J. The heat Q ~ W delivered to the gap d in time $\Delta t = 2d/c$ is,

$$Q = \frac{U}{\Delta t} = N\frac{h}{4}\left(\frac{c}{d}\right)^2$$

The near-field time $\Delta t = d/2c$ is the same as the NP time $\tau = d/2nc$ having n = 1.

A. tBLG Heat Transfer

In 2021, heat flux Q in near-field heat transfer [5] based on temperature fluctuations in tLBG not only showed a 10-fold increase over only a few degrees of twist, but also predicted specific angles θ of peak heat flow. Fig. 7 shows the heat transfer coefficient (HTC) exceeded the BB limit by 5 orders of magnitude.

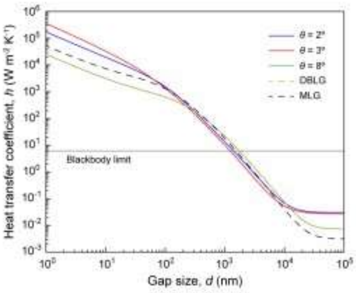

Figure 7. HTC of tBLG from [5]

Further, Fig. 7 shows gap d = 100 μm with the BB limit at 1 μm. In contrast, simple QED based on the Planck law requires the kT energy of the atoms in tBLG surfaces to vanish in order to conserve heat by EM waves instead of temperature. The Planck law at 300 and 15 K is shown in Fig. 8.

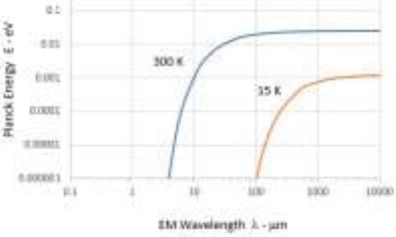

Figure 8. Planck law at 300 and 15 K

At 300 K, Fig. 8 shows vanishing kT may be taken as E = 1×10^{-6} eV at λ = 4 μm which is 4 orders of magnitude less than kT = 0.0254 eV at λ > 200 μm, the latter corresponding to classical physics where heat Q does increase temperature. Hence, the maximum allowed gap d < λ/2 = 2 μm. Simple QED for d < 1 μm is compared with the θ = 3° twist in Fig. 9.

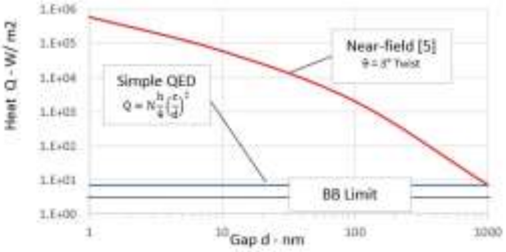

Figure 9. Near-field Comparisons

The assumption in Fig. 9 is the same power P is applied to each gap d meaning that N/d^2 is conserved. From Fig. 7, for d_1 = 1000 nm: Q = 7 Wm^{-2} and $N_1 = 4.7\times10^5 \rightarrow N = N_1/(d_1/d)^2$ for other gaps. Fig. 9 shows simple QED does not enhance the heat flow Q over the BB limit for all gaps compared to the 5 orders of magnitude reported [5] for tBLG.

B. Cryogenic Near-field

In 1970, the near-field effect in enhancing radiative heat transfer [11] in large gaps d < 500 μm was based on shifting of the Planck law to longer wavelengths at liquid helium temperatures. Consistent with simple QED, the Planck function at long wavelengths λ < 1000 μm at 15 K is shown in Fig. 8.

Cryogenic near-field research continues today [12] on the same basis [1-5, 11] of thermally induced fluctuating temperatures. The measurements were conducted with plane parallel gaps at temperatures from 10 to 40 K as shown in Fig. 10.

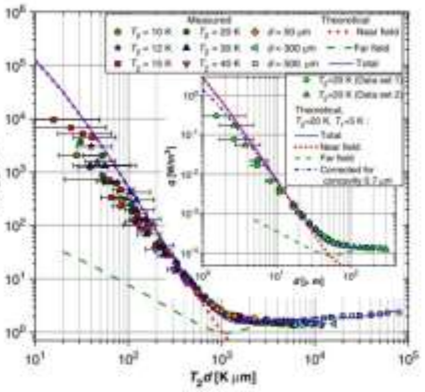

Figure 10. Cryogenic Near-field

The validity of simple QED is limited to the wavelengths λ where the Planck law shows the kT energy of the atom is orders of magnitude lower than that at which classical kT heat capacity allows temperature to change. Taking 15 K as representative of [12] experiments, Fig. 8 shows λ < 100 μm or macroscopic gaps d < λ/2 = 50 μm may be used to study near-field effects using simple QED.

Indeed, simple QED was applied to Fig.10 (inset) data from 1 to 50 μm assuming the same heater power P was used at all gap settings. Because of the thinking that temperature controls the near-field, temperature is usually reported and not the applied P. Fig. 11 assumes the P applied at all gaps is the same as that for the gap d = 50 μm.

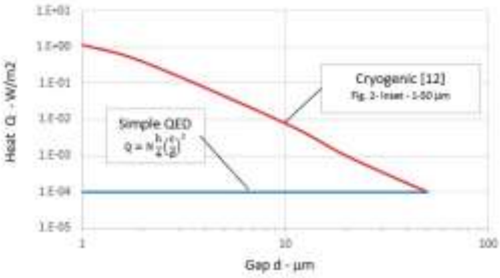

Figure 11. Cryogenic Near-field comparison

Simple QED is observed to provide the same heat flow Q at all gaps compared 4 orders of magnitude for near-field theory based on temperature fluctuations.

C. Near-field Heat Source

Simple QED differs from near-field theories in that the heat flow Q is the same for all gaps and there is no enhancement above the BB limit. Indeed, comparing near-field theories by the increase in heat Q flow above the BB-limit has no meaning as a nanoscale gap lacks a source of energy to be a heater, e.g., a nanoscale gap in a 1-D rod does not increase the heat flow along the length.

In this paper, the suggestion that near-field experiments report the power P delivered to a nanoscale gap instead of temperature would highlight the fact the gap does not increase the heat Q transfer. In simple QED, the measured heat Q = P ~ W provides a mechanism by which the number N of EM waves created across the gap d conserve the heat Q flow. The heat flux Q/A ~ Wm^{-2} has no meaning as the number N of EM waves does not depend on gap area A.

V. CONCLUSIONS

In nanoscale gaps, the Planck law denies the existence of temperature fluctuations, plasmons, polaritons, and evanescent waves.

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

Only temperature independent near-field theories are valid at the nanoscale, one such theory is simple QED explicitly based on the Planck law.

Simple QED applied to tBLG conserves heat flow while temperature fluctuation theory increases heat flow 5 orders of magnitude above the BB limit

Small tLBG twist angles cause Moire' fringes between layers, but Moire' fringes are not likely to increase heat transfer across the gap by 10 orders of magnitude.

The size dependent gap validity in simple QED known a half-century ago allowing near-field effects to be observed in macroscopic gaps was assessed by considering the shift in the Planck law to longer wavelengths at cryogenic temperatures. At 15 K, simple QED conserves heat flow while temperature fluctuation theory predicts 4 orders of magnitude increase over the BB limit.

Experiments of near-field effects should report the power P delivered at each gap size as temperature alone is not sufficient to show nanoscale gaps do not increase actual heat flow.

Near-field heat transfer research is suggested to focus on temperature independent mechanisms.

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