QED Induced Near-Field Radiation

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ABSTRACT: Planck's theory of BB radiation stands as one of the greatest achievements of science in that the dispersion of the EM emission of photons with wavelength (or frequency) was shown to depend solely on the temperature of the material. BB stands for blackbody and EM for electromagnetic. More fundamentally, Planck's theory also provided the basis for quantum mechanics (QM). At the macroscale, Planck's theory has served well in predicting radiative heat transfer provided the gap or separation between heat transfer surfaces is large compared to the wavelength of the emitted EM radiation. However, experimental data for nanoscale gaps between flat plates unambiguously show near–field enhancement of heat transfer above that given by Planck theory consistent with the QM enhancement of the near field by standing wave QED photons in the theory of QED induced radiation. QED stands for quantum electrodynamics. Analysis is presented showing QM conserves the heat in the Stefan-Boltzmann (S-B) equation by creating standing QED photons between gap surfaces that transfer heat at the speed of light making the far slower phonon polaritons at acoustic velocities inconsequential in near field radiative heat transfer.

KEYWORDS: Planck, **b**lackbody radiation

I. INTRODUCTION

Planck's theory [1] of BB radiation stands as one of the greatest achievements of all time in that the dispersion of the EM emission of photons with wavelength (or frequency) was shown to depend solely on the temperature of the material. Moreover, Planck's theory also provided the basis for QM. At the macroscale, Planck's theory has served well in predicting radiative heat transfer provided the gap or separation between heat transfer surfaces is large compared to the wavelength of the emitted thermal radiation. With regard to radiative heat transfer between surfaces separated by nanoscale dimensions, Planck never claimed his theory was applicable contrary to reports [2] that that Planck theory sets an upper limit on heat transfer at the nanoscale.

Planck probably knew high frequency thermal photons standing across nanoscale gaps are far more efficient than those at the long wavelengths of the macroscale. It is unlikely therefore, that Planck would have imposed a limit on the maximum BB radiative heat transfer between surfaces at the nanoscale. Nevertheless, experimental data [2, 3] for nanoscale gaps between flat plates unambiguously show near–field enhancement of heat transfer above that given by Planck theory. In fact, the data is consistent with the QM enhancement of the radiative near field by standing wave QED photons in the theory of QED radiation.

II. BACKGROUND

Planck's theory of BB radiation giving the dispersion of EM radiation emitted from the surface of a material provided a simple explanation of experiments based on QM that depended solely on the temperature of the material. One consequence of Planck's theory is the S-B equation,

$$Q = \sigma A(T_H^4 - T_C^4) \quad (1)$$

where, σ is the S-B constant, A is the surface area, T_H and T_C are the absolute temperatures of the hot and cold surfaces.

Of interest is application of the S-B equation to radiative heat transfer between surfaces separated by nanoscale gaps including QM effects. In contrast, classical EM theory [4, 5] of radiative heat transfer at the nanoscale is thought [2, 3] to occur by evanescent surface phonons. Typically, the heat flux is found to increase inversely with the square of the gap dimension.

However, the argument [6] has been made that as the gap vanishes, the heat flux diverges, and therefore power conservation is not conserved. The first counter argument [7] is that divergence of the flux is precluded because a thermal contact is established so that the radiative resistance tends to zero, and therefore the heat flux must be finite because there no longer is any temperature difference. As a theory, however, evanescent heat transfer assumes there is always a gap without thermal contact, and therefore the temperature difference remains constant as the gap vanishes, thereby supporting the argument [6] that power conservation is indeed violated. Only if the heat flux does not diverge as the gap vanishes is evanescent theory a valid description of nanoscale radiative heat transfer.

In this regard, a second counter argument [7] against divergence in evanescence theory is shown to depend 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 a nonlossy and lossy material, the heat transfer is bounded. The latter is of no consolation to the validity of evanescent theory as radiative heat transfer still diverges for lossy materials, thereby placing in question the validity of evanescent theory itself.

Yet the more fundamental difficulty with evanescent theory is that phonons transfer heat at acoustic velocities. Compared to QED photons standing across the gap and transferring heat at the speed of light, phonons are simply too slow to be of any consequence in the conservation of radiative heat transfer between surfaces at nanoscale separations.

What this means is heat transfer is conserved by QED photons before phonons even "think" of contributing to the heat transfer. A single QED photon standing across the gap d is shown in Fig. 1. The hot and cold temperatures are T_H and T_C. The QED photon is depicted to penetrate distance e into the hot and cold surfaces.

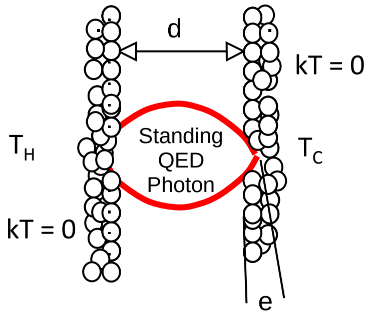

Fig. 1 Standing wave QED photon.

III. THEORY

A. QM Restrictions

The QM restrictions on the kT energy of the surface atoms depend on EM confinement. At 300 K, the Einstein-Hopf relation [8] for the atom as a harmonic oscillator gives the QM restriction with wavelength λ as shown in Fig. 2.

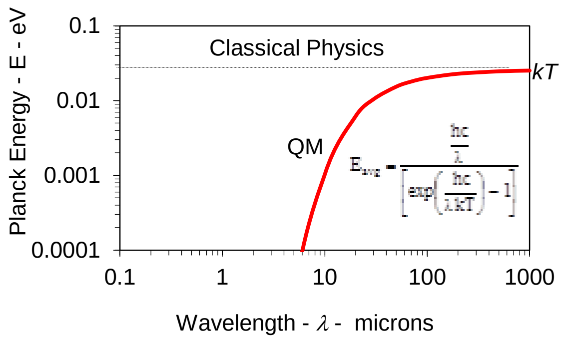

Fig. 2 Harmonic Oscillator at 300 K

In the inset, h is Planck's constant, c is the speed of light, k is Boltzmann's constant and T is absolute temperature.

QED photons induced by EM confinement may be understood from Fig. 2. For λ > 100 microns (d > 50 microns), the atom has heat content given by the kT energy. At gaps < 50 microns, the heat content is insignificant and vanishes at the nanoscale. Unlike classical physics, QM precludes the atom from conserving absorbed EM energy at the nanoscale by an increase in temperature.

B. EM Confinement Frequencies

The EM confinement of the QED photon in the gap d between surfaces is analogous to creating photons of wavelength λ in a QM box with walls separated by λ/2. The EM confinement frequency f, wavelengthλ, and Planck energy E,

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

IV. ANALYSIS

QM by Planck's theory given by the Einstein-Hopf relation for the harmonic oscillator limits the kT energy 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 λ = 2(d+2e) with the QED photon penetrating to depth e in each surface. From Fig. 2, QM requires the atoms have vanishing kT energy at EM confinement wavelengths < 6 microns. Hence, QM requires kT = 0 for atoms in surfaces having gaps d < d +2e < 3 microns.

What this means is QM negates the notion of surface temperature in the S-B equation for d < d + 2e < 3 microns, i.e., the S-B equation can no longer conserve the radiative heat flow Q by the temperatures T_H and T_C of the hot and cold surfaces.

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

$$N_p = \frac{\sigma A}{q}(T_H^4 - T_C^4) \qquad (3)$$

corresponds to the number of QED photons required to conserve the S-B heat flow Q. Taking d + 2e = 3 microns to correspond to large gaps where the S-B equation is applicable, the QED heat flow Q_{qed} is:

$$Q_{qed} = \sigma A(T_H^4 - T_C^4)\left(\frac{3}{d + 2e}\right)^2 \qquad (4)$$

For d >> 2e, Q_{qed} increases inversely with the square of the gap d consistent with the near–field enhancement observed [2, 3] in experiments. The Q_{qed} response depends on the QED photon penetration e into the surface. In order to fit the Q_{qed} response to the Q_{exp} data [2] at d = 0.01 microns, the penetration depth 2e was found to be 0.035 microns. The Q_{qed} and Q_{exp} comparison including the number N_p of QED photons created is shown in Fig. 3.

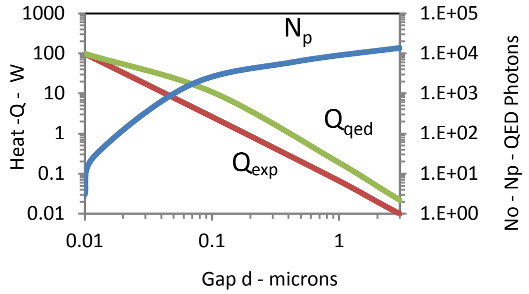

Fig. 3 QED response and Experiment

In the QED simulation, the area A = 0.000126 m^2. For quartz glass [2], the optical absorption in the UV and beyond is negligible, and therefore the penetration 2e should be >> 0.035 microns. Fig. 4 gives Q_{qed} corrected for estimated optical absorption of quartz showing convergence to about 1 W at d < 0.1 microns.. Divergence of Q_{qed} inherent to evanescent theory is not observed. The S-B heat of 0.02 W is therefore enhanced in QED theory to a factor of about 50.

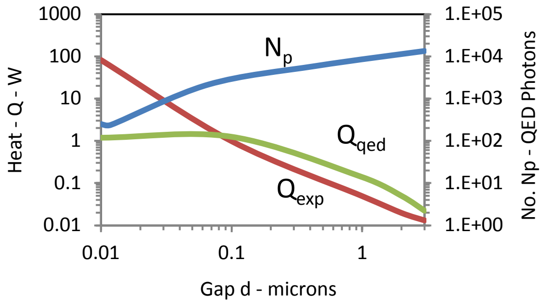

Fig. 4 QED heat corrected for quartz absorption

In contrast, the experimental data [2] showing divergence as d vanishes suggests a review of the evanescent theory and experiment is recommended.

V. SUMMARY

1. QED induced heat transfer provides a simple theory for near-field enhancement perfectly consistent with Planck's QM and theory of BB radiation. Classical electromagnetics theory based on tunneling of evanescent waves by phonon surface polaritons that differ conceptually from the QM embodied in Planck's theory cannot be expected to explain near-field enhancement.

2. Near-field heat transfer by evanescent waves shows the heat flux varies inversely with d squared, and therefore as d vanishes, the heat flux diverges. With evanescent waves, divergence occurs because the heat transfer depends on whether the media is lossy or nonlossy, a condition that is not readily known thereby questioning the applicability of any evanescent theory. In contrast, Qqed also gives an inverse d squared dependence, but differs in that there is no divergence because the standing QED photons penetrate distance e below the surface, i.e., Qqed converges to $h(c/2e)^2$ as d vanishes upon surface contact.

3. Conservation of radiative heat transfer by QED photons in nanoscale gaps is prompt making the far slower evanescent waves by phonons inconsequential to near-field heat transfer.

4. The source of QED photons in the gap finds basis in the QM requirement that the kT energy of the atoms under EM confinement in surfaces at ambient temperature vanishes at (d+2e) < 3 microns. Lacking kT energy, the atoms cannot increase in temperature, and therefore the heat given by the S-B equation can only be conserved by the EM emission into the gap that by QED is induced to create QED photons. For the same hot and cold temperatures, the QED heat flow is enhanced above that of Planck theory.

REFERENCES

[1] M. Planck, Theory of Heat Radiation, Dover Publications, Inc., New York, 1959.

[2] A. Narayanaswamy, et al., "Breakdown of the Planck blackbody radiation law at nanoscale gaps," Appl Phys A, 96: 357–362 (2009)

[3] R. S. Ottens, et al., "Near-Field Radiative Heat Transfer between Macroscopic Planar Surfaces," PRL 107, 014301 (2011)

[4] D. Polder, M. Van Hove, Phys. Rev. B 4, 3303 (1971)

[5] S. M. Rytov, et al. *Principles of Statistical Radiophysics* (Springer, Berlin, 1987)

[6] J. L. Pan, "Radiative transfer over small distances from a heated metal," Optic Letters, 25, 369 (2000)

[7] J-P Mulet, et al., "Comment on 'Radiative transfer over small distances from a heated metal'," Optics Letters, 26, 480 (2001)

[8] A. Einstein and L. Hopf, "Statistische Untersuchung der Bewegung eines Resonators in einem Strahlungsfeld," *Ann. Physik*, 33, 1105 (1910)