The QED Induced Electrostatic Force

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Abstract *– Recent claims that the thermal Casimir force has been observed are questionable because of the significant charge created by the photoelectric effect from the conversion of thermal energy of atoms in gap surfaces to photons by quantum electrodynamics (QED).To obtain the thermal Casimir force, the unwanted electrostatic forces were removed by applying a servo-controlled compensating voltage to minimize the potential across the gap. Therefore, the measured forces is not the sought after thermal Casimir force, but rather the servo modified ubiquitous QED induced electrostatic force ever present in all Casimir experiments.*

1 Introduction

Over 50 years ago, Casimir [1] derived the attractive force between neutral conductive flat plates separated by an evacuated gap by extending the zero point energy (ZPE) of quantum mechanics (QM) to the field.

Casimir relied on Planck's derivation [2] of the law for blackbody (BB) radiation that included the ZPE. In terms of the average Planck energy E_{avg} of the atom as a harmonic oscillator,

$$E_{avg} = \frac{\frac{hc}{\lambda}}{\exp\left(\frac{hc}{\lambda kT}\right) - 1} + ZPE \qquad (1)$$

where, ZPE = ½ hc/λ. Here, h is Planck's constant, λ the oscillator wavelength, k Boltzmann's constant, c the speed of light, and T absolute temperature.

In contrast, the Einstein-Hopf derivation [3] of the BB radiation law excludes the ZPE,

$$E_{avg} = \frac{\frac{hc}{\lambda}}{\exp\left(\frac{hc}{\lambda kT}\right) - 1} \qquad (2)$$

Unlike Planck, Einstein did not think the field ZPE existed. However, Casimir did, but never thought the gaps between neutral surfaces would charge let alone undergo electrostatic discharge (ESD). Contrarily, Casimir force experiments show significant charge is produced by otherwise neutral surfaces. In fact, the Casimir force measurements [4] that ostensibly verified the ZPE were swamped [5] by ESD, as the mirrors had to be kept neutral by first touching them together before each measurement was made.

Nevertheless, the field ZPE continued to be thought to exist. Boyer's classical derivation [6] of the field ZPE agreed with Planck. Moreover, Boyer even argued the experimental [4] verification of the Casimir effect affirmed the existence of the ZPE. But the argument is moot if the Casimir force is caused by a mechanism other than the field ZPE.

Casimir's pair of plane mirrors was simulated [7] by a chromium-coated silicon plate and a flat surface of a cantilever beam separated by a gap from 0.5 to 3 μm. Between parallel plates, the Casimir force F_c is,

$$F_C = \frac{\pi hcA}{480d^4} \qquad (3)$$

where, A is the area of the plates, and d is the separation between the plates. By noting the change in resonant frequency of the beam with the gap, the Casimir force was claimed proven within 15%.

Today, flat plates are not used in Casimir experiments because of the difficulty in alignment. Instead, the interacting surfaces are usually [8-12] taken as a sphere-plane geometry, the sphere being the tip of the AFM. The Casimir force F_c in the sphere – plane geometry AFM geometry is given by,

$$F_c = \frac{\pi^2 hcR}{360d^3} \qquad (4)$$

where, R is the radius of the sphere.

A. Validity of the Field ZPE

The ZPE more commonly called the energy of the vacuum is thought to pervade all of space as a field. But Planck's treatment of the ZPE of atoms in a crystal or molecule differs from the ZPE of the field in the vaccuum. Today, the ZPE has been verified in molecular spectra, but there is no verification for the ZPE of the field. Indeed, Jordan and Pauli [13] argued that since the ZPE is neither absorbed nor reflected, it could not be detected, and therefore the field ZPE was unverifiable. Regardless, the ZPE of the field is clearly unphysical because of the infinite energy it creates as the wavelength vanishes, i.e., ZPE = ½ hc/λ → ∞, as λ → 0.

In a letter to Einstein, Jordan stated the ZPE is just a quantity of the calculation having no direct physical meaning. Einstein agreed, and in a letter to Ehrenfest stated: "I tend to the opinion that the ZPE of the field is wrong. A ZPE of cavity radiation should not exist." See references in [14].

Nevertheless, Casimir chose to base his derivation of attractive force between neutral plates on the controversial ZPE of the field

B. Gap Sensitivity

One Casimir experiment [8] using the sphere-plane geometry measured the Casimir force in the 0.6 to 6 μm range. The sphere was a 4 cm diameter spherical lens and a 2.5 cm diameter optical flat, the optical surfaces gold coated. The Casimir force was found sensitive to gap size with a noticeable change in the Casimir force not occurring until the gap reached the 0.6 μm lower limit.

Similarly, the Casimir force was determined [9] with an AFM using a gold coated 200 μm sphere and flat over gaps from 0.1 to 0.9 μm. The Casimir force was only found to change at gaps below about 0.2 μm. Another Casimir experiment [10] over a range from 0.1 to 1 μm was also found sensitive to gaps below 0.2 μm.

Casimir's theory excluded conditions on gap size sensitivity. A relevant question is:

Why gaps $d < 0.2$ μm are important
for significant Casimir force?

C. Electrostatic Discharge

ESD has always been a problem [4] with measurements of the Casimir force or anytime a submicron gap is formed between otherwise neutral surfaces. In a MEMS device, a gold coated beam [11] having a rectangular protrusion was positioned to form a gap with a flat electrode. The Casimir force loaded the beam, and after time the beam contacted the electrode, the contact causing the fusion of the electrode along the full length of the protrusion. Since the Casimir induced contact pressure is estimated [5] to be very small, about 1 bar at 10 nm, it may be safely concluded that fusion induced by high pressure did not occur. What this means Is that charge is created in otherwise neutral surfaces separated by nanoscale gaps, i.e., the fusion in MEMS devices caused by ESD.

In 1948, Casimir could not have envisioned the ESD observed [12] some 50 years later from otherwise neutral semiconductor materials in photolithography. Today, ESD is a common problem in 0.25 μm and below production lines. The question may be asked:

How is charge created in neutral materials
separated by submicron gaps ?

D. Thermal Casimir Force

Casimir experiments performed at ambient temperature have generally confirmed the Casimir force at gaps less than about 0.2 μm. However, it is not clear whether the measured Casimir forces are caused by the field ZPE or have thermal origin.

The thermal Casimir forces derived in the Lifshitz [15] formalism are the Drude and Plasma models,

$$F_D = \frac{\zeta(3)}{8}\frac{RkT}{d^2} \qquad F_P = \frac{\zeta(3)}{4}\frac{RkT}{d^2} \qquad (5)$$

where, F_D and F_P stand for Drude and Plasma forces, ζ is the Riemann zeta function, $\zeta(3) = 1.202$. Since the thermal Casimir forces vanish at zero T, the field ZPE may be confirmed if the Casimir force in (3) is measured within a few mK of absolute zero.

E. Charging Mechanisms

Contrary to Casimir's notion of the ZPE, experiments [4-11] unequivocally show charge is created in the gap between otherwise neutral plates. Analogous to sphere-plane Casimir experiments, charge is created [16] in vibrating AFMs. The likely AFM charging mechanism [17] is thought to be field electron emission.

However, field emission of electrons across gaps requires an applied electric field contrary to Casmir's notion that the ZPE field alone causes the attractive force. Moreover, field emission lacks the sensitivity to gaps < 0.2 microns as electron tunneling occurs at any gap provided a sufficiently high electric field is applied. A more fundamental mechanism independent of an applied electrical field is required to explain the charging observed in Casimir experiments.

F. Proposed Charging Mechanism

About a decade ago, the ZPE Casimir force was proposed [18-20] to be electrostatic based on the charge created by the QED induced photoelectric effect in gaps < 0.2 μm where the photons have sufficient Planck energy to charge the plates. The QED induced electrostatic force as then measured [4-12] is therefore electrostatic induced by QED having nothing to do with the field ZPE.

The electrostatic Casimir force is the consequence of QED inducing the thermal kT energy of atoms in the plate surfaces to create QED photons in the gap that have sufficient Planck energy to charge the plates by the photoelectric effect.

G. Recent Casimir Experiments

Recently, the Casimir force based on the field ZPE is claimed supported by experiments [20,21]. The experiments are noteworthy in that the claims are inconsistent with Pauli's [13] and Einstein's [14] arguments that the field ZPE does not exist. Moreover, the thermal Casimir force at finite temperature that differs from Casimir's field ZPE force at absolute zero is also claimed measured. Both experiments use the sphere–plane contact geometry, distinguished only by the type of sensor, i.e., the AFM or torsion pendulum.

G.1 AFM Sensor The AFM sensor [21] is excited at resonance and upon the cantilever tip being brought in close proximity to the flat, the attractive force changes the frequency. However, this force is not the thermal Casimir force alone, but includes electrostatic forces. Indeed, the electrostatic forces are significant and a bias voltage is continually controlled by a servo during sensor force measurements to minimize the electrostatic force. Unlike the early static [4] Casimir experiments that create charge once just as the gap decreases to submicron dimensions, the AFM creates charge every time the vibration amplitude forms submicron gaps with the flat surface. The AFM measurements of Casimir force were made at 300 and 4.2 K.

G.2 Torsion Pendulum The torsion pendulum [22] measures the attractive force in the gap between the sphere with the plate attached to the pendulum thereby applying a torque that is counteracted by a pair of `compensator' electrodes. A servo loop applies the compensator electrode voltage necessary limit pendulum oscillations about the stationary position that correspondingly causes the gap to fluctuate. The attractive force is then proportional to the compensator electrode voltage necessary to keep the pendulum stationary. The plate is grounded and a bias voltage is continuously applied to the sphere to correct for electrostatic forces. However, charge is created anytime the gap fluctuations become submicron. Measurements of the thermal Casimir force are made at 300 K.

2 Purpose

The purpose of this paper is to show what is thought to be the thermal Casimir force measured in experiments [21,22] is nothing more than electrostatic force from charge created by the QED induced photoelectric effect.

Not only is the thermal Casimir force questioned but so also Casimir's notion of the field ZPE as the source of the attractive force between neutral plates.

2. Theory

The QED induced photoelectric Casimir force considers the creation of QED photons from the thermal kT energy of atoms in the surface of the gap. The QED photons standing in the gap d are depicted in Fig. 1.

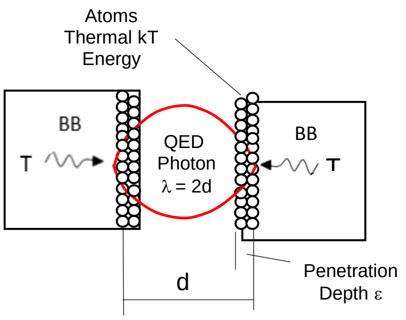

Fig. 1 QED induced Photoelectric Effect

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The creation of QED photons continually depletes the thermal kT energy of the surface atom that is replenished by BB radiation from the plates at bulk temperature T. Many surface atoms are available to create the QED photons that penetrate the gap surfaces to depth ε.

2.1 Thermal Origin

The QED induced photoelectric effect finds origin in the thermal kT energy of the atoms on the gap surfaces. In the Einstein-Hopf [3] relation for the atoms as harmonic oscillators, the average Planck energy E_{avg} at 300 K as a function of wavelength λ is shown in Fig. 2.

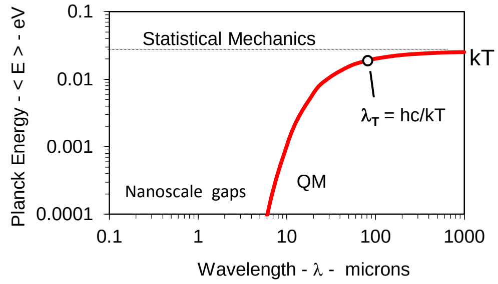

Fig. 2 Harmonic Oscillator at 300 K

By the equipartition theorem of statistical mechanics, the classical oscillator allows the atom in gap surfaces to have the same heat capacity as the macroscale. QM oscillators differ in that kT energy is only available for $\lambda > \lambda_T$. At ambient temperature, atoms in gap surfaces having d < 0.1 micron or λ < 0.2 microns have virtually no heat capacity to conserve heat from BB radiation by an increase in temperature.

2.2 QED Electrostatic Force

The QED electrostatic force finds origin in the thermal kT energy of the atoms in gap surfaces. The number N_{QED} of QED photons created having Planck energy E is conserved with the number N_A of surface atoms,

$$N_{QED}E = \frac{3}{2}kTN_A \qquad (6)$$

where, E = hc/2d. By the photoelectric effect, the QED photons create charge density σ = Q/A depending on the yield Y of electrons per photon

$$\sigma = \frac{Q}{A} = \frac{N_{QED}}{A}Ye = \frac{3kTdYe}{hc}\frac{\eta}{\Delta^2} \qquad (7)$$

where, A is plate area, Q is charge, and e is the electronic charge. The number N_A of surface atoms as the fraction η of area A assumes Δ is the cubical atomic spacing, typically Δ ~ 0.25 nm. At 300 K, the yield Y of gold [23] increases abruptly at QED photon energies E ~ 5 eV or gaps d ~ 120 nm and saturates to about 9 eV at 70 nm gaps. The yield of gold at 4.2 K could not be found in the literature and for the purposes here was taken to be that at 300 K as shown in Fig. 3.

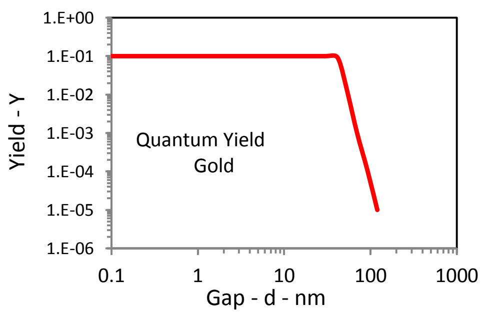

Fig. 3 Quantum Yield of Gold at 300 K

For the AFM sensor and pendulum having contact areas A < 1 cm^2, the fraction η of surface atoms at 300 and 4.2 K needed to create 1 pC charge is given in Fig.4.

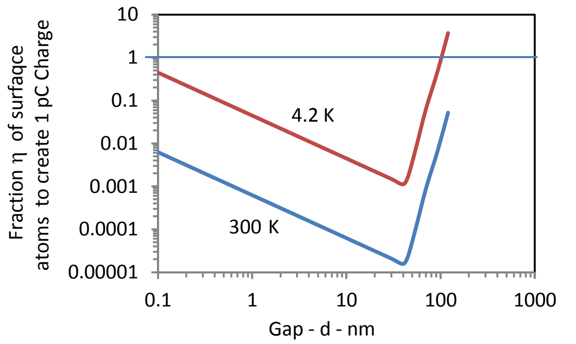

Fig. 4 QED Induced Charge

At 300 K, Fig. 4 shows η < 1 for all d, but at 4.2 K, η > 1 for d > 100 nm. However, charging at 4.2 K still occurs because the gap under AFM vibrations always closes, i.e., at d < 70 nm, the yield Y = 0.1 electrons/QED photon. Like the Drude and Plasma models, the QED force vanishes at T = 0.

The QED force F_{QED} is determined from the charge density σ by combining (6) and (7),

$$\sigma = \frac{Q}{A} = \frac{N_{QED}}{A} Ye = \frac{3kTdYe}{hc} \frac{\eta}{\Delta^2} \qquad (8)$$

Giving,

$$\frac{F_{QED}}{A} = \frac{\sigma^2}{2\varepsilon_o} = \frac{1}{2}\varepsilon_o \frac{V^2}{d^2} \qquad (9)$$

where,

$$V = \frac{\sigma d}{\varepsilon_o} \qquad (10)$$

The F_{QED} force gradient,

$$\frac{G}{R} = 2\pi \frac{F_{QED}}{A} \qquad (11)$$

The QED induced charge density σ and voltage V corresponding to the G/R force in (Fig. 3 of [21]) is shown in Fig. 5. For G/R ~ 1 N/m^2, σ ~ 1.8×10^{-6} C/m^2 and V ~ 0.07 V. The voltage V depicted assumes the charge Q is created at d = 120 nm.

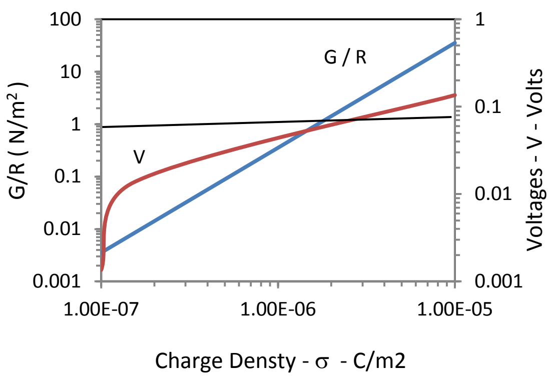

Fig. 5 QED Charge Density and Voltage

2.3 Photoelectric Current

The BB radiation at temperature T necessary to balance the rate $\dot{N}$ of standing wave QED photons created having Planck energy E is,

$$E\dot{N} = 2\sigma_o A T^4 \qquad (12)$$

where, σ_o is the Stefan-Boltzmann constant.

$$\frac{\dot{N}}{A} = \frac{4d\sigma_o T^4}{hc} \qquad (13)$$

The QED induced photoelectric current density I/A is,

$$\frac{I}{A} = \frac{\dot{N}}{A} eY \qquad (14)$$

The current densty I / A is shown in Fig. 6.

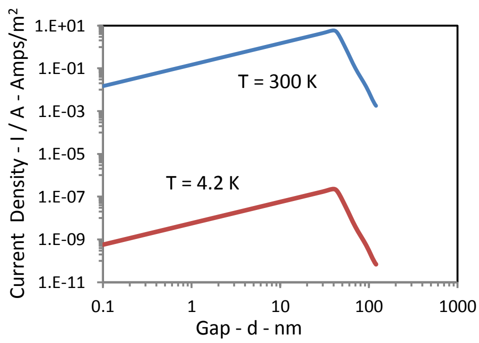

Fig. 6 QED Current Density

3. Discussion

3.1 Electrostatic Casimir Force

3.1.1 AFM Sensor The QED induced electrostatic force is proposed to be both Casimir's force [1] based on the field ZPE and the recently discovered [22] thermal Casimir force. Consistent with Pauli and Einstein [13,14], Casimir's force does not exist, and therefore what has been measured in ZPE Casimir experiments to date is the QED induced electrostatic force. To show this, consider the following argument:

The AFM sensor is a sphere-plane geometry, but is assumed [20] as the force per unit area F_{pp}/A in plane-plane (PP) configuration, the quantity usually calculated by Casimir theory. The force gradient G/R is,

$$\frac{G}{R} = 2\pi \frac{F_{PP}}{A} \qquad (15)$$

In the PP configuration, the force F_{PP}/A is,

$$F_{PP} = \frac{1}{2} C \frac{V^2}{d} \qquad (16)$$

where, C is the capacitance, $C = A\varepsilon_o/d$.

Giving,

$$\frac{F_{PP}}{A} = \frac{1}{2}\varepsilon_o \frac{V^2}{d^2} \qquad (17)$$

The force F_{pp}/A is strictly electrostatic following the classical inverse square law with the gap d. The voltage V source ensures that charge Q is always equal to the product C*V by adjusting the charge while the gap is changing. Between voltages V and V_o, maintaining the same charge $Q = Q_o$ requires,

$$Q = CV = C_o V_o = Q_o \quad \text{or} \quad V = \frac{d}{d_o} V_o \qquad (18)$$

Increasing the gap therefore increases the voltage, i.e., $d > d_o \rightarrow V > V_o$. Since the thermal Casimir force is not thought to be electrostatic, the servo is made to compensate for the electrostatic force by minimizing the voltage across the gap. In effect, the servo is driven by the inverse of (18) giving,

$$V = V_o \frac{d_o}{d} \qquad (19)$$

Substituting (19) into (17) gives,

$$\left(\frac{F_{PP}}{A}\right)_{Servo} = \frac{1}{2}\varepsilon_o \frac{1}{d^2}\left(\frac{V_o d_o}{d}\right)^2 = \frac{1}{2}\varepsilon_o \frac{V_o{}^2 d_o{}^2}{d^4} \qquad (20)$$

Servo-control therefore changes the classical inverse square $1/d^2$ law in (17) to the inverse fourth power $1/d^4$ law in (20). Although similar to the Casimir force for perfect mirrors in (3), the QED force is electrostatic caused by the servo having nothing to do with the field ZPE. Absent the servo, the QED induced force follows the $1/d^2$ law of classical electrostatics.

The QED force in relation to Casimir's inverse fourth power law over gaps from 0.1 to 1000 nm and a detailed plot from 100 to 1000 nm is shown in Figs. 7 and 8, respectively.

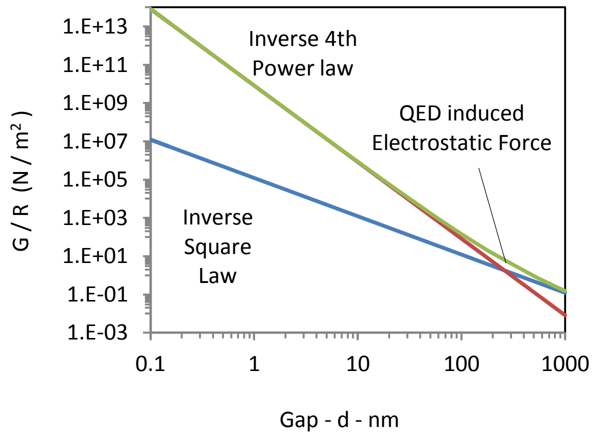

Fig. 7 QED Induced Electrostatic Force
Range 0.1 - 1000 nm
Color – Online: QED force – green,
Inverse 4th Power – red, and Inverse Square - blue.

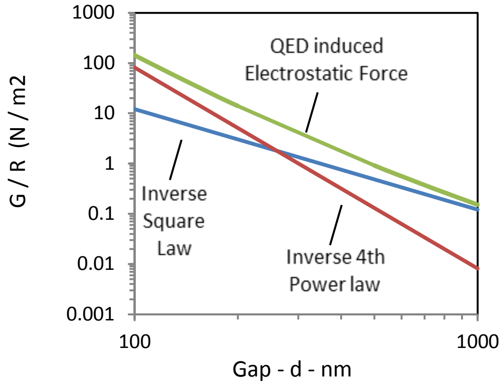

Fig. 8 QED Induced Electrostatic Force at 300K
Range 100 - 1000 nm

Fig. 8 shows the QED induced force is in close agreement with (Fig. 3 of [21]) as the G/R force follows the $1/d^2$ law for d > 100 nm converges to the $1/d^4$ law for d < 100 nm.

Unlike the Lifshitz theory for Casimir force at 4.2 K shown in (Fig. 7 of [21]) that gives 50% lower values than the data, the QED force accurately follows the 4.2 K data form 100 to 1000 nm as shown in Fig. 9.

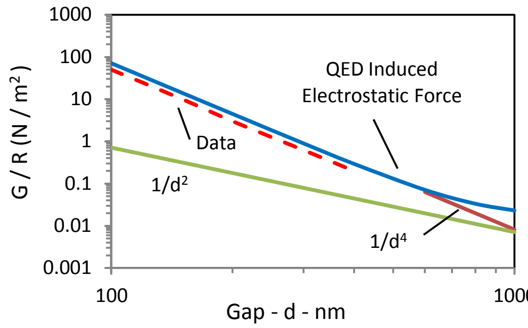

Fig. 9 QED Induced Electrostatic Force at 4.2 K
Range 100 - 1000 nm
Color – Online: QED force blue, Data red dashed
$1/d^4$ red solid and $1/d^2$ green.

The color legend in Fig. 9 shows the QED force as the blue curve from 100 to 1000 nm. The Au-Au data (Fig. 7 of [21]) from 100 to 400 nm is coincident with the QED force, but is shown as the dashed red line displaced downward for clarity. The classical electrostatic force (17) varying as $1/d^2$ is shown as a green curve from 100-1000 nm. The servo generated $1/d^4$ curve is coincident with the QED force at d < 600 nm, but is only shown for clarity as a solid red line for d > 700 nm.

Again, the notion Casmir's force exists has prompted ways of removing the extraneous charges in the surroundings to obtain Casimir's $1/d^4$ curve for perfect mirrors. The fact of the matter is the extraneous charges are the source of what is thought to be the Casimir force caused by the field ZPE, i.e., the $1/d^4$ behavior is the consequence of having the servo remove the unwanted electrostatic forces and has nothing to do with Casimir's force based on the field ZPE.

3.1.2 Torsion Pendulum The torsion pendulum [22] experiment like the AFM Sensor [21] uses a servo to minimize the electrostatic potential in preserving the $1/d^2$ behavior for gaps d > 0.7 microns as shown in (Fig. 2 of [22]). Over this range, the thermal Casimir force is thought to dominate. Unlike the AFM sensor with plane-plane contact that under servo control showed a transition from $1/d^2$ to $1/d^4$ behavior, the torsion pendulum transition with sphere-plane contact from $1/d^2$ to $1/d^3$ behavior is not presented.

Instead, the emphasis [22] is placed on the controversy over the question whether the thermal Casimir force is Drude or Plasma. However, the question may be moot.

Given the long history of charge in Casimir experiments, it is more likely the thermal Casimir force is actually the QED induced electrostatic force for only a few 100 electrons. To show this, the number N_E of electrons required to produce the thermal Casimir force is estimated for discrete charges Q,

$$F_{QED} = \frac{1}{4\pi\varepsilon_o}\frac{Q^2}{d^2} \qquad (21)$$

where, $Q = N_E\, e$.

The charge Q and number N_E of electrons in the QED force necessary produce the average of Drude and Plasma forces is,

$$Q = N_E e = \sqrt{\frac{2\pi\varepsilon_o\zeta(3)RkT}{3}} \qquad (22)$$

At 4.2 and 300 K, the number of electrons N_E ~ 88 and 740 as illustrated in Fig. 10.

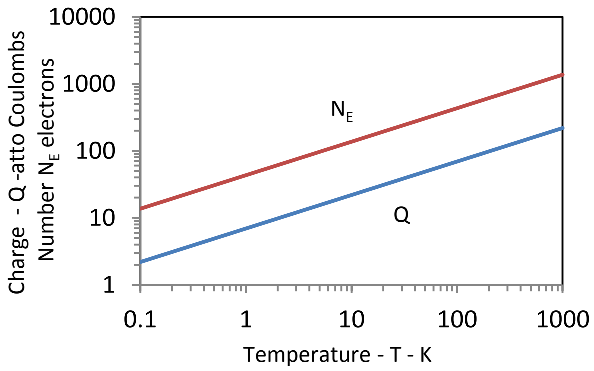

Fig. 10 QED Induced Electrostatic Force

Irrespective of whether the Drude or Plasma force is correct, the number N_E of electrons is very small and cannot be distinguished in the sea of electrons being created by QED. Simply put, Lifshitz theory cannot compete with the magnitude of QED induced electrostatic forces. There is no need to consider extraneous sources of charge by patches [24] of surface crystalline structure, adsorbed impurities or oxides. In fact, the patches are QED induced charges.

3.2 Existence of the Field ZPE

The temperature dependence of the Casimir force is important in assessing the existence of the field ZPE. If Casimir's field ZPE theory is correct, the Casimir force at 4.2 K should be very close to that in (3) for perfect mirrors at 0 K. Indeed, the Au-Au data (Fig. 7 of [21]) shows it is close to that for perfect mirrors. However, the thermal Casimir force by the Drude model at 4.2 K is not close, but rather 50% lower than the data. It can only be concluded the ZPE Casimir force appears to be confirmed at 4.2, but not the thermal Casimir force given by the Lifshitz theory.

However, the reason the ZPE Casimir force appears to be verified needs to considered. Equating the servo force (20) with the ZPE Casimr force (3) gives,

$$V_o d_o = \sqrt{\frac{\pi hc}{240\varepsilon_o}} \qquad (23)$$

The voltage V_o at gap d_o that gves the ZPE Casimir relation is shown in Fig. 11.

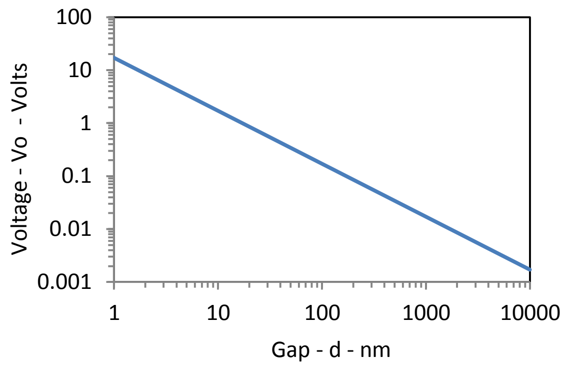

Fig. 11 Voltage V_o at Gap d_o to verify ZPE Casimir

The QED force for the 4.2 K dat in Fig. 9 was obtained by trial and error by varying V_o at d_o = 1000 nm until a visual match of V_o = 0.016 V was found to verify the ZPE Casimir force. Fig. 11 shows the exact match is V_o = 0.017 V. Other V_o values do not give a good match and the ZPE Casimir theory would not be verified.

4. Summary and Conclusions

The application of QED induced electrostatic force to the thermal Casimir effect yields the following conclusions:

➢ Casimir's extension of Planck's ZPE of QM to the field is verified in the AFM sensor tests [21] at 4.2 K by a fortuitous choice of the voltage created from the residual charge at large gaps, but otherwise the ZPE Casimir at 4.2 K is not verified. However, the thermal Casimir force at 4.2 K is 50% lower than the data. More study is suggested to confirm these conclusions.

➢ The force being measured in Casimir experiments is electrostatic because ALL experiments conducted to date [4-11,21,22] show ESD. One need not go further to conclude Casimir's notion of an attractive force between neutral plates is in conflict with reality.

➢ The only scientific interest in Casimir's force is the mechanism by which otherwise neutral plates charge upon being brought close together.

➢ Experiments showing the Casimir force to be sensitive to gaps d < 0.2 μm are explained by the abrupt increase of the photoelectric yield of most materials to QED photons having Planck energy E > 5 eV.

➢ The dynamic Casimir experiments [21,22] produce far more charge than early static [4] experiments because every time the gap closes to submicron dimensions, the QED photons in the gap create charge. Photoelectrons having high-energy are trapped beneath the gold surface and cannot be easily removed by applying minimizing potentials < 100 mV.

➢ The controversy [22] whether the Drude or Plasma models give the best estimate of thermal Casimir force is resolved – neither do. Instead, the thermal Casimir force is the QED induced electrostatic force created from the thermal kT energy of the gap surface atoms.

➢ Servo control to remove the QED electrostatic force leaving only the neutral ZPE force needs review. Perhaps, a return to the early static [4] tests is required.

➢ The observation of the $1/d^4$ law in [21,22] does not mean Casmir's field ZPE in (3) has been verified, but rather is an artifact of the servo-controlled minimization potential. Servo-control can indeed follow the inverse $1/d^4$ law. but has nothing do with the field ZPE. Absent servo-control, the QED induced electrostatic force follows the $1/d^2$ law of classical physics. Statements [21,22] that the data infer the validity of the ZPE Casimir force given by perfect mirrors are simply erroneous.

➢ QED induced radiation is proposed as the mechanism of charging neutral plates separated by nanoscale gaps. QED radiation based on QM offers physical explanations of behavior at the nanoscale not possible with classical physics. See numerous QED applications [25].

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