Two Kinds of Vacuum in Casimir Effect

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

The Casimir effect is one observable of the existence of the vacuum energy, i.e. the existence of vacuum electromagnetic field. The meaning of this word "vacuum" is physical vacuum, not technology vacuum. Then, we say that the change in the vacuum structure enforced by the plates. There are two kinds of vacuum, one is usual vacua or free vacua (outside the plates). Another is the negative energy vacua (inside the plates), and the refraction index less than 1(n<1). That cause a change in the light speed for electromagnetic waves propagating perpendicular to the plates: $\triangle c/c \cong 1.6 \times 10^{-60} d^{-4}$, and d is the plate distance. When $d=10^{-9}$m(1nm), $\triangle c=10^{-24}c$. Then, a two-loop QED effect cause the phase and group velocities of an electromagnetic wave to slightly exceed c. Though the difference are very small, that raise interesting matters of principle. The focus of this paper is to improve the understanding of the nature of quantum vacuum. In the past, to say that "vacuum is not empty" was already a criticism and subversion of classical physics. Now it seems doubly strange to say that there is a negative energy vacuum that is "empty"than the normal physical vacuum. But these theories are rigorously justified; Casimir effect can create an environment with refractive index less than 1(n<1) and lead to the appearance of superluminality, which is one of the representations of "quantum superluminality". These advances in basic science will certainly open up new fields of application, In short, it is not the Casimir structure that creates the quantum vacuum, but the structure that makes the quantum vacuum "emerge"in a clever way as a perceptible physical reality. This is truly a scientific achievement.

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1. INTRODUCTION

In 1948, Dutch physicist Hendrik Casimir discovered a physical phenomenon known as Casimir effect [1-5]; It has been widely valued and studied for a long time [6-10]. This is because it provides a direct demonstration and proof that "quantum vacuum is a physical reality". The basic way to demonstrate the Casimir effect is to take two neutral (uncharged) metal plates, place them parallel to each other, and the two will attract each other. The two plates form an electromagnetic boundary environment, but in classical physics, there is no electrodynamic reason for mutual attraction to actually occur. Therefore, Casimir effect is a quantum effect. In quantum field theory (QFT), there is the so-called zero point energy (ZPE), which represents the infinite energy of a vacuum state; Casimir first proposed a method to produce a finite result for this infinite vacuum, namely Casimir force; And it can be traced back to the famous van der Waals force.

In fact, Casimir began his theoretical work by studying van der Waals forces, and it was N.Bohr who advised him to consider the effects of ZPE. Interestingly, it was not until 1997 that the Casimir force was actually measured experimentally, and in the following 20 years, the Casimir effect was studied and applied. From the perspective of scientific innovation, it has brought important enlightenment and instructive benefit to people

2. THE VACUUM VIEW OF MODERN PHYSICS

Matter always exists in various forms, independent of our consciousness; Even distinct forms of matter must be rational. Vacuum is an objective reality, a form of matter. In a broad sense, vacuum is the largest and universal existence in the universe. In narrow engineering terms, a vacuum is the result of a human quest to live at the bottom of the atmosphere, where pressure is highest. The essence of this quest is the acquisition of local, airless environments in a small container by vacuum pump equipment and the measurement of such environments by sensing means. This is the practice of engineering vacuum.

For physical vacuum, The British physicist Dirac put forward the following viewpoint in 1928:

vacuum is a state in which the negative energy level is occupied by all electrons; Or in other words, the vacuum is filled with electrons in the negative energy level. In the past, vacuum was regarded only as an empty region of space. Dirac adopted a new concept that a vacuum is a region of space with the lowest possible energy; There are only two ways to get the non-vacuum state: one is to fill an electron into the positive energy state; The other is to create a hole in the distribution of negative energy states. The hole actually means a particle with the same mass as the electron, but with a positive charge. His theory received little attention at first, but positrons were discovered in 1932. It was Dirac that started the idea of a physical vacuum.

In 1974, the idea emerged that if there was an extremely strong force field, the energy stored in the force field could produce particles in a vacuum. For example, when a strong magnetic field above 10^6 Gs is applied to a vacuum, a kind of particle with photonic properties but with rest mass—heavy photon is produced. It has a short lifetime and will decay into an electron-positron pair.

There are signs that the nature of vacuum is not a simple problem. Nobel Laureate Dr Lee Chung-do said in 1979: "Vacuum is a real thing, a medium with Lorentz invariance. Its physical properties can be expressed through the interaction of elementary particles."

Therefore, from the perspective of modern physics, vacuum should no longer be called "space without any matter". Logically, such a space does not exist. The exact definition of vacuum (physical vacuum) is: the lowest energy state (ground state) of a system of quantum field, which is the basic form of matter's existence; Matter particles are nothing more than the product of the vacuum excited state, the ground state is no real particles. However, the generation, disappearance and transformation of virtual particles in the vacuum reflect that all modes in the quantum field are still oscillating in the ground state (zero-point vacuum oscillation). The complexity of physical vacuum can be seen from the following research topics: vacuum condensation, vacuum polarization, vacuum symmetry breaking, vacuum phase transition, etc. Some people suggest that we should discuss it in two general directions: first, the nature of vacuum

itself; The other is the nature of the interaction between vacuum and particles.

Back to engineering vacuum. Here, the engineering definition of a vacuum is: "A rarefied gas state with a pressure less than 1 atm." The vacuum degree is mainly expressed in pressure units: the lower the pressure, the higher the vacuum degree, A unit of pressure expressed by the height of the mercury, i.e, the pressure of a gas in terms of length, based on Torricelli's 1644 mercury barometer experiment. This unit has long been used in industry. From a practical point of view, it is very convenient to have a scale to measure the pressure. But millimeters of mercury are not a very deterministic unit. Mercury variety, purity, temperature and other factors affect its density value, thus affecting the definition. The Torr, a unit adopted in honor of the Torricelli, is similar in size to millimeters of mercury (the Torr is 7×10^{-6} smaller than mmHg). In the International system of Units(SI), the unit of pressure is Pascal(symbol Pa), whose magnitude is $1Pa = 1N/m^2 = 1kg/(m \cdot s^2)$; However, 1 atm=101325Pa, so 1Torr=1 atm/760=133.332Pa. Despite this, the Torr unit is still used in many scientific laboratories. From 1953 to 1970, humans ability to obtain a vacuum had reached 10^{-8} to 10^{-13} Torr, which is called ultra-high vacuum(UHV). By the end of the 20th century, this ability had increased to $p \leq 10^{-14}$ Tor, which is called extremely high vacuum(EHV).

When physicists talk about ZPE, the vacuum is, of course, a physical vacuum, not an engineering vacuum. The Casimir effect is the expression engineering vacuum condition(the an pressure in the exporimental environment) has on effect on the experiment, that is, the measurement of Casimir force should be carried out in the engineering vacuum environment, and even the UHV condition should be guaranted. But past experimenters in the literature have not done so, which is puzzling. In any case, there is still plenty of room for improvement in existing experiments.

3. THEORETICAL BASIS OF ZERO POINT ENERGY [11-13]

Does a vacuum have energy? It's not an easy question to answer. We know that the engineering definition of "vacuum" is "vacuum is a rarefied gas with a pressure of less than 1 atm(101325Pa)". However, the long-standing philosophical and scientific understanding of a vacuum is that it is an empty space (or state), which equates "vacuum" with "no matter".

Scientific developments in the 20th century led to the realization that there is no such thing as a "complete absence of matter". Since matter is related to energy, "the vacuum energy is zero prime no longer makes sense. This is a popular statement of the idea that a vacuum has energy.

However, in the vocabulary used by people, energy comes from energy and has the characteristics of output and application. It is in this understanding that the terms "electricity energy", "wind energy", "solar energy", "nuclear energy" are used. If the term "vacuum energy" is put forward alongside them, it looks very suspicious on the face of it. Therefore, the scientific community is not unanimous on the concept of "vacuum energy". One view is that ZPE cannot be used at all because it represents the lowest quantum state and is not an "acquired energy". Another view puts forward the slogan of "ask for energy from vacuum", and thinks that the zero-point energy (ZPE) measured by Los Alamos laboratory in 1997 is at least measurable.

Let us review the basic theory of quantum mechanics (QM) combined with statistical mechanics. The energy of a single quantum of energy(photon) amount for

$$E = \hbar \omega = hf \tag{1}$$

Where $\hbar = h/2$, h is a Planck constant. In long time the experiments have shown that a photoelectric receiver based on the photoelectric effect always receives only the quantity of energy mentioned above formula or a multiple there of; None of the instruments that attempted to "split the photon" succeeded, i.e. the "partial photon" did not exist. The conclusion is clear, it is impossible for monochromatic wave photons to split into two photons of the same frequency, each carrying only part of the original photon, i.e., no photon of energy $hf/2$ exists (it is impossible to split a photon into two photons with half the original energy).

But QM tells us something else. As a result of the uncertainty principle, it is impossible to leave a microscopic particle at rest at its lowest potential energy. A quantum field can be regarded by Fourier analysis as a superposition of harmonic oscillators of different frequencies, so that it has energy even in the ground state (i.e. a physical vacuum). That is, in the lowest energy state (ground state), the energy of a harmonic oscillator at a frequency f is $hf/2$. Although it cannot be output, it is indeed energy. Quantum

electrodynamics (QED) is used to quantize electromagnetic field. Firstly, vector potential is introduced as the regular coordinate, then the regular momentum is derived, then the regular coordinate and momentum are converted into operators, and finally the Hamilton operator of single-mode electromagnetic field is given. Thus, the electromagnetic field is transformed into a photon field, and the state of the electromagnetic field is represented by the photon number state (the eigenstate of the Hamilton operator).

Using the Coulomb guide, vector potential A satisfies the wave equation:

$$\nabla^2 \boldsymbol{A} = \frac{1}{c^2}\frac{\partial \boldsymbol{A}^2}{\partial t^2}$$

The Hamiltonian quantity is obtained from the canonical momentum, i.e

$$H = \int \frac{1}{2}(\varepsilon_0 E^2 - \mu_0 H^2)\, dV$$

H in the integral sign is the magnetic field strength. And now we going to expand it with orthogonal modular functions, we obtain:

$$\boldsymbol{A} = \sum_{i=1}^{2}\sum_{k}\sqrt{\frac{\hbar}{2\varepsilon_0\omega_k}}\left[a_{ki}\boldsymbol{U}_{ki}(r)e^{-j\omega_k t} + a_{ki}^*\boldsymbol{U}_{ki}^*(r)e^{j\omega_k t}\right] \quad (2)$$

Where, i is two polarization directions; Is wave vector, wave number $k_0 = \omega\sqrt{\varepsilon_0\mu_0} = \omega/c$, so We have:

$$\omega = ck \quad (3)$$

However, the momentum (vector) of the electromagnetic wave quantum of wave vector k is $p=\hbar k$ the amplitude is

$$p = \hbar k_0 = \frac{hf}{c}$$

The energy (scalar) of this quantum is $E = \hbar\omega = hf$.

Now the generalized momentum can be obtained from $\prod = \varepsilon_0 \boldsymbol{A}$ and become an operator, so

$$\boldsymbol{A} = \sum_{ki}\sqrt{\frac{\hbar}{2\varepsilon_0\omega_k}}\left[\hat{a}_{ki}\boldsymbol{U}_{ki}(r)e^{-j\omega_k t} + \hat{a}_{ki}^+\boldsymbol{U}_{ki}^*(r)e^{j\omega_k t}\right] \quad (4)$$

$$\prod = \sum_{ki}(-j)\sqrt{\frac{\hbar\varepsilon_0\omega_k}{2}}\left[\hat{a}_{ki}\boldsymbol{U}_{ki}(r)e^{-j\omega_k t} + \hat{a}_{ki}^+\boldsymbol{U}_{ki}^*(r)e^{j\omega_k t}\right] \quad (5)$$

After quantization, the Hamilton operator is

$$\hat{H} = \sum_{ki}\hbar\omega_k\left[\hat{a}_{ki}^+\hat{a}_{ki} + \frac{1}{2}\right]$$

Where, $\hat{a}_{ki}^+$ is the photon's generation operator; $\hat{a}_{ki}$ is the annihilation operator of photons. It's easier to write:

$$\hat{H} = \sum_{k}\hbar\omega_k\left[\hat{a}_{ki}^+\hat{a}_{ki} + \frac{1}{2}\right] \quad (6)$$

The commutation relation is

$$\left[\hat{a}_k \cdot \hat{a}_{k'}^+\right] = \delta_{kk'}$$

The photon number state representing the photon field is

$$\hat{H}\left|n_k\right\rangle = \hbar\omega_k\left[n_k + \frac{1}{2}\right]\Bigg|_{n_k} \quad (7)$$

The photon number operator (k mode) is

$$\hat{n} = \hat{a}_k^+ \cdot \hat{a}_k$$

In the above types, $\left|n_k\right\rangle$ represents the state of n_k photons, and the average value of the light field is 0.

The same conclusion as equation (7) can be obtained by using the method of quantization of harmonic oscillator. In general, the quantized electromagnetic field is described by the eigenstate $\left|n_k\right\rangle$ of the photon number operator, which represents the states containing n_k photons(k mode). Can be expressed by the simpler formula below, that is, for the single-mode electromagnetic field:

$$\hat{H} = \hbar\omega\left[n + \frac{1}{2}\right] \quad (8)$$

Where, n is the number of photons. Thus, the energy of k-mode electromagnetic field is not $n\hbar\omega$, but one more term. When there are no photons in space (n=0), the energy of k-mode is not zero, but $\hbar\omega/2$, which is ZPE; Its discovery is the achievement of the quantization theory of electromagnetic field itself. Vacuum is now regarded in quantum theory as the ground state, denoted as $|0\rangle$. The energy of the ground state is

$$\langle 0|H|0\rangle = \frac{1}{2}\sum_k \hbar\omega_k \tag{9}$$

It's actually saying that the ZPE quantity is.

$$E_0 = \frac{1}{2} hf \tag{10}$$

In Equation (8), when n=0(vacuum without photon), there is still a minimum energy E_0. Therefore, a quantum subsystem without quantum still has a minimum energy, whose value is exactly 1/2 of the energy carried by a quantum, namely ZPE. It must be noted that ZPE is independent of temperature; ZPE is independent of n(the state of the quantum system); ZPF is consistent with the spontaneous emission of the system (ZPE causes spontaneous emission). hf/2 only means that each existing mode has a radiation density equivalent to half a quantum energy, but does not mean that there can be "half a quantum" or "half a photon".

Now let's look at the harmonic oscillator analysis when statistical mechanics is combined with QM. If the temperature drops to T=0K(thermodynamic zero), it is impossible for microscopic particles not to have any motion. Otherwise, its momentum and position can be determined precisely at the same time, thus violating the Heisenberg uncertainty relation. In fact, when T=0K, the microscopic particles still vibrate. This phenomenon can be obtained by calculating and expounding the average energy of several harmonic oscillators by means of statistical mechanics, so the result is:

$$\overline{E} = \frac{hf}{e^{hf/kT}-1} + \frac{1}{2} hf \tag{11}$$

Equation (11) is the Planck black-body radiation formula. It is the result of combining statistical mechanics and quantum theory, and also the basis of quantum noise theory and stimulated radiation theory. The unit of E is J or W s, or W/Hz. In electronics terms, it's the spectral power density, which is power per unit of bandwidth. The first term at the right end of equation (11) is the average energy of an oscillating mode at frequency f, and the second term is ZPE. That's because when we take T equals 0K, the first term is 0, and we're left with the second term.

In short, the average energy, or the power spectral density of thermal fluctuation and thermal radiation, caused first term on the right side of Equation (11). The second term is independent of temperature T, it's still there even by vibration (oscillation) of any substance at equilibrium temperature T above absolute zero is expressed by the if T is equal to 0K, which means there's still one term of energy at absolute zero. Make

$$p(f) = \frac{hf/kT}{e^{hf/kT}-1} \tag{12}$$

There are

$$E = kT\left[p(f) + \frac{1}{2}\frac{hf}{kT}\right] \tag{13}$$

So E depends on the ratio of hf to kT. In fact, this ratio reflects the ratio of quantum effect to classical effect, and the larger the ratio is, the larger the quantum effect is (it cannot be ignored). The author calculated the relationship between the value of p(f) and hf/kT (Table 1). In fact hf/kT>0, so always p(f)<1; The question is how much less than one. Obviously, the higher the frequency and the lower the temperature, the lower the p(f).

The above is the basic understanding of zero point energy (ZPE), but more macroscopic discussion is needed.

Table 1. Relationship data of p(f) and hf/kT

hf/kT	0	0.1	0.2	0.5	1	2	3	4
p(f)	1	0.9506	0.9033	0.7708	0.5820	0.3130	0.1572	0.075

4. ABOUT VACUUM ENERGY [14-16]

For single mode electromagnetic field, we already know that the Hamilton operator is

$$\hat{H} = \hbar\omega\left[n + \frac{1}{2}\right];$$ Therefore, when there is no

photon (n=0) in space, the mode energy is not zero, but E_0 =hf/2, which was originally proved by P. Dirac and became the basic knowledge of QM.

The key now is to understand the nature of a vacuum; vacuum has energy fluctuations, this fluctuation of energy can be understood as virtual matter. In short, there must be energy fluctuation caused by interaction in vacuum without concrete matter according to uncertainty principle. In this sense, vacuum is a physical medium or complex system, which is one of the important achievements of quantum theory.

It must be noted that the vacuum fluctuations cannot be stopped by taking away their energy, because they have no energy. Sometimes there may be positive energy borrowed from somewhere else, and as a result there may be negative energy, which in turn rapidly absorbs energy from the positive energy region, thus reducing it to zero or maintaining some positive energy. The vacuum fluctuation is stimulated and driven by this continuous energy borrowing process. In the field of electromagnetic and electromagnetic waves, as well as in the field of laser technology, vacuum fluctuations have an experimental basis, and a term "spontaneous emission" has been used to call them.

If the vacuum energy density is assumed to be ρ_0 , ρ_0 will be infinite if integrated over all frequencies according to the ZPE formula. Even if the integration of all frequencies is not reasonable, ρ_0 must be very large (J. Wheeler estimates ρ_0 up to 10^{35} J/m^3). Assuming that the vacuum in the universe has energy, it becomes a source of gravity, creating a gravitational field. Thus, cosmological studies on the large scale are linked to quantum field theory studies on the small scale. Years ago, astronomers reported finding that the expansion of the universe was accelerating, One readily available explanation is Einstein's cosmological constant. Sure, a vacuum can produce a repulsive force, but how much? Quantum field theory holds that random fluctuations in energy produce short-lived virtual particles at a constant rate. However, the vacuum energy is so great that the repulsive force applied is 10^{120} times greater than known. Some particles have negative energy, so excess is spared, leaving only a tiny residual energy that could explain the acceleration seen.

But the scientific community is divided on "vacuum energy". One view is that zero point energy cannot be exploited at all because it represents the lowest quantum state and is not an "acquired" energy. Another view puts forward the slogan of "energy from vacuum", and thinks that the (10-15)J energy obtained by the measurement of Casimir force by Los Alamos laboratory in 1998 is zero point energy or vacuum energy. Reports were mixed, however, and some described the measurement as proof of "negative energy."

As is well known, Newton's gravitational field equation takes the form of Poisson's equation, the 2nd order linear partial differential equation of the gravitational potential:

$$\nabla^2\Phi = 4\pi G\rho \qquad (14)$$

Where, ρ is the density of matter and represents the source of the gravitational field. In 1915, Einstein proposed the equation of gravitational field [1]:

$$R_{\mu\nu} - \frac{1}{2}R_{\mu\nu}^g - \lambda g_{\mu\nu} = -8\pi G T_{\mu\nu} \qquad (15)$$

Here, T is the momentum-energy tensor of the gravitational source, $g_{\mu\nu}$ is the space-time metric, and $R_{\mu\nu}$、 R is the tensor composed of the metric and its derivative. λ is the cosmological term and is known as the cosmological constant. In recent years, λ has been referred to as the repulsive factor. Scientific developments in the 20th century have continued into the early 21st century, and many things are related to λ .

From purely mathematical point of view, it's easy to solve this equation by taking λ minus 0. Therefore, The Einstein field equation is also written as:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = -\kappa T_{\mu\nu} \qquad (16)$$

Where, g is the metric tensor; R is the curvature tensor; κ is a coefficient proportional to Newton's gravitational constant:

$$\kappa = \frac{8\pi G}{c^2} \qquad (17)$$

In 1921, Einstein gave a lecture at Princeton University in the United States using formula (16).

In 1917, astronomers discovered that most spiral nebulae were receding from the Milky Way at great speeds. In fact, the action that a vacuum can produce is a repulsive force, which is consistent with the term "repulsive factor". This can be proved mathematically, and only through the equations of general relativity (GR) can we see it more clearly. GR theory gives the dynamic equation of uniform isotropic universe as

$$\ddot{R} = -\frac{4\pi}{3}G(\rho - 2\rho_{eff}R) \qquad (18)$$

Where, ρ is the average density of the universe; ρ_{eff} is the effective cosmic density considering cosmological constant and vacuum energy density; ρ_{eff} is defined as

$$\rho_{eff} = \rho_0 + \frac{1}{8\pi}\frac{\lambda}{G} \qquad (19)$$

These mathematical formulas provide the entrance to the basic theory of cosmology. The negative sign before the second term in parentheses on the right of equation (18) indicates that the action of ρ_{eff} is opposite to that of ρ, that is repulsion; The source of repulsion can be obtained from equation (19): the first is the positive cosmological constant($\lambda > 0$). and the second is the vacuum energy density ($\rho_0 > 0$).

That's just a summary. The real cosmological study (which will determine) is very complex. In the discussion of these problems, scientists have many puzzles and problems to be solved. Moreover, if GR is incorrect, the above discussion is invalid. To be clear, the fact that we have introduced Einstein's theories does not mean that I agree with Einstein.

The vacuum energy problem has not been settled in the scientific community. However, scientists have put forward many suggestions and made various efforts. In 1984, R. Forword suggested using the phenomenon of cohesion of charged thin film conductors to extract electrical energy from a vacuum. In the early 20th century, Cartan and Myshkin independently proposed that there is a long range interaction in nature — torsion field. Later this idea was widely studied [17]. In combination with ZPE, vacuum ZPE is considered to be the energy of the torsion field. The torsion field is considered to be caused by the spin of the object and the disturbance caused by spin transverse polarization of vacuum. In 1997, A.Akimov and G.Shipov [18] proposed in their paper on the torsion field that it is possible to extract energy from the vacuum by eddy perturbation of the physical vacuum. Interestingly, according to Dubrovsky's research, the propagation speed of the torsion field is considered to be superluminal ($v > 10^9 c$). In 2000, it was reported that someone found evidence of the existence of the torsion field in electrolysis experiments. In early 2001, an international conference on "field propulsion technology" was held in the UK. One of the topics on the agenda was "the possibility of using ZPE to propel spacecraft". Such spacecraft, if realized, could fly freely in space for long periods of time without carrying fuel. This idea is based on the understanding of vacuum (a physical vacuum is an ocean of infinitely large fluctuations of energy) and the idea that energy can be extracted anywhere in space as long as the dynamic Casimir effect is coherent with the torsion field. Researchers believe that the 21st century may be the century of successful implementation of ZPE [19].

The research of Chinese scientists shows that the introduction of torsion field theory and the in-depth study of physical vacuum will help to understand the abnormal exothermic and nuclear phenomena in electrochemical processes [20-23]. In the electrolysis process, microbubbles constantly appear at the electrode tip or micro-bulge. The formation, growth and collapse of bubbles are dynamic processes at the cavity boundary. Under resonance conditions, dynamic Casimir effect will occur and ZPE will be absorbed. The supernormal exotherm observed during electrolysis is not mainly due to the exotherm of nuclear reaction, but by extracting

ZPE. The phenomenon of superheat is caused by two mechanisms: the torsion field generated by vortex plasma and the vacuum ZPE coherence and the dynamic Casimir effect.

5. CASIMIR FORCE OF A PAIR OF PARALLEL METAL PLATES [24, 25]

Casimir was a Dutch physicist. What led to his famous discovery? It all started with van der Waals forces. By the 1940s, H.Casimir(1906-2000), a scientist at Philips Laboratories in the Netherlands, and his colleagues carried out further research, the results of which were collected in three papers published in 1948 and 1949. For example, two interacting atoms can be regarded as two oscillators with a distance of d. In this case, the degenerated natural frequency, 0 decomposed into $\omega = \omega_0\sqrt{1+k}$, where k is the coupling strength of the oscillator, which is proportional to d^{-3}. If a portion of ZPE ($\hbar\omega/2$) is allocated to each frequency, the interaction energy is obtained:

$$E \propto \frac{\hbar\omega_0}{d^6} \qquad (20)$$

However, T. Overbeek of the Philips Institute found some problems in his experiments, arguing that London's calculations were improper in assuming that electromagnetic interactions were instantaneous. If the finiteness of the speed of light (the speed of electromagnetic action) is taken into account, the van der Walls potential should be corrected over large distances. Overbeek approached Casimir and D. Polder, who devoted themselves to the problem. First analyze a simpler system, in which a single atom is in an electromagnetic cavity made of an ideal conducting wall. Calculate the interaction between the atom and the nearest cavity wall and find out how it relates to distance. After quantum electrodynamics (QED) processing of the field inside the cavity, they concluded that atoms are attracted to the wall of the cavity. This force came to be known as the Casimir-Polder force [1], with an associated energy of:

$$E_c = -\frac{3}{8\pi}\frac{\hbar c\alpha}{d^4} \qquad (21)$$

Where: α is electrostatic polarization; Casimir and Polder went on to calculate the attraction energy between two atoms, and found that if two atoms were identical, it would be

$$E_c = \frac{23}{4\pi}\frac{\hbar c\alpha^2}{d^7} \qquad (22)$$

Casimir later wrote," I mentioned my work to Bohr on a walk; He said it was good, it was creative work. I told him that I was puzzled by the simplicity of the formula for action over large distances; He pointed out that this may be related to ZPE. That was all it was, but it was a new road for me."

Casimir recalculated, assigning a ZPE ($\hbar\omega/2$) to each mode of the cavity, again using the well-known perturbation formula for cavity mode frequency:

$$\frac{\delta\omega}{\omega} = -2\pi\alpha\frac{\left|E_0(x_0, y_0, z_0)\right|^2}{\int\left|E_0(x, y, z)\right|^2 dV} \qquad (23)$$

Here (x_0, y_0, z_0) is the position of the particle in the cavity, and the integration is performed over the total volume of the cavity. The energy is now determined by the sum of all the modes in the cavity, and the energy of attraction can be obtained by taking the energy difference between the two particles and the wall. Casimir's method can be said to reduce the problem of quantum electrodynamics to that of classical electromagnetism. Casimir finally gets the force between the walls of the cavity, which is caused by the zero-point field of the cavity.

This is the theoretical background that led to Casimir's discovery, but it does not yet map out the exact path to success. The key element of Casimir's scientific thinking is that only certain virtual photons are counted when calculating the energy between two uncharged conductor plates, Each mode contributes a pressure to the plate, and the external infinite mode has a higher pressure than the internal infinite mode, which creates a force that brings the plates together. Experimental evidence of this force has been evidence of a vacuum electromagnetic field, improving our understanding of the vacuum. Now we say that is a quantum vacuum effect.

Imagine that two metal plates are placed in parallel at a distance of d (Fig.1). According to the analysis of electromagnetic field theory, there are two transverse polarization modes, TE and TM, for each wave number (k) of the bowl. From the point of view of guided wave theory, it is a parallel plate waveguide structure, which may

have TEM modes and a series of TE$_{mn}$ and TM$_{mn}$ higher-order modes. Subscripts m and n are called indexes of modes, which can generally be understood as discrete, but do not exclude the continuous change of mode indexes in some cases, unless the index is zero.
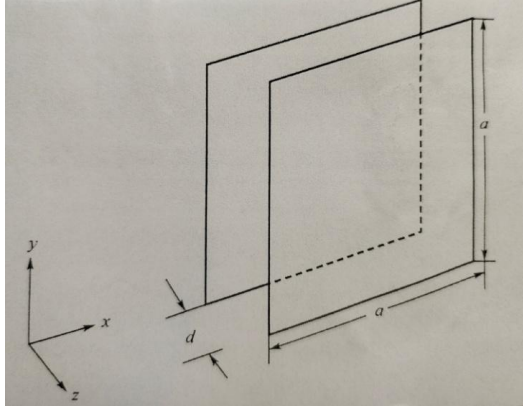

Fig.1 . Schematic diagram of Casimir force

In Casimir's case, the situation was different: he was talking about the macroscopic quantum phenomenon of ZPE changes caused by the presence or absence of a boundary, so he was comparing the absence of parallel plates (free space) with the presence of plates (boundary). The wave vector (k) parallel to the plate does not differ with or without the plate; But the wave vector(k$_\perp$) perpendicular to the plate is discrete (n is a discrete positive integer) with the plate and continuous (n changes continuously) without the plate. One dimensional analysis is easier to do, where the coordinates are taken as follows: the x and y axes are close to the surface of one of the plates, and the z axes are perpendicular to the plate (another metal plate is placed at z=d). In this case, the wave vector is perpendicular to the material surface and its magnitude is

$$k = \frac{n\pi}{d} \qquad (24)$$

Let the same space have two cases respectively: free space without plate (no cavity), ZPE energy is E_{fr} (subscript fr is the first two letters of free); A space with a plate(cavity)and an energy of E_{cav} (subscript cav is the first three letters of cavity). The energy difference between the two cases is

$$\Delta E = E_c = E_{cav} - E_{fr} \qquad (25)$$

The subscript c stands for Casimir, that is, the difference represents a particular kind of Casimir energy, i.e. E_c. If $E_c \neq 0$, it means that ZPE changes after the insertion of the cavity (such as two metal plates). If $E_c < 0$, it can be known that $E_{cav} < E_{fr}$, that is, ZPE becomes smaller after the insertion of the cavity. Such as E_c (absolute value) is related to cavity wall spacing (d), then the occurrence of force can be judged, which is the cause of Casimir force. In classical physical theories, such as Maxwell's electromagnetic field theory, there is neither the concept of ZPE nor the generation of Casimir forces. Therefore, this energy and this force are both products of Quantum Field Theory. If it can be proved by experiments, the correctness of relevant theories can be expressed in reverse.

In 2000, R.London [26] provided a simple and straightforward derivation. The following will be elaborated according to his ideas. When the electromagnetic field to be quantanization, the radiative Hamiltonian is

$$\hat{H}_r = \sum_k \sum_\lambda \hbar\omega_k \left[\hat{a}_{k\lambda}^+ \hat{a}_{k\lambda} + \frac{1}{2} \right] \qquad (26)$$

Where, the subscript *r* represents radiation. Introducing the above vacuum definition, the energy eigenvalue equation is

$$\frac{1}{2} \sum_k \sum_\lambda \hbar\omega_k \left\| 0 \right\rangle = E_0 \left\| 0 \right\rangle$$

So we get the vacuum energy

$$E_0 = \frac{1}{2} \sum_k \sum_\lambda \hbar\omega_k = \sum_k \hbar\omega_k \qquad (27)$$

The two polarities (TE and TM) have been summed here.

Consider that space has a one-dimensional system (parallel double conductor plates) whose existence only gives rise to discrete modes. The boundary conditions require the mode group density k=nð/d, so the cavity energy (ZPE) can be written as

$$E_{cav} = \sum_k \hbar ck = \frac{\pi\hbar c}{d} \sum_{n=1}^{\infty} n \qquad (28)$$

Where: c is the speed of light. When there is no board in the same space, discrete n is replaced by a continuous variable:

$$E_{fr} = \frac{\pi \hbar c}{d} \int_0^\infty n \, dn \qquad (29)$$

Therefore, a

$$E_c = \frac{\pi \hbar c}{d} \left[\sum_{n=1}^\infty n - \int_0^\infty n \, dn \right] \qquad (30)$$

Euler-Maclaurin summation formula is used to obtain

$$E_c = -\frac{\pi \hbar c}{12d} \qquad (31)$$

Find the attraction between the two plates is

$$F_c = \frac{\partial E_c}{\partial d} = \frac{\pi \hbar c}{12d^2} \qquad (32)$$

The above derivation may seem banal, but it was the first to show (in the simple-dimensional case) how a finite (small) change can occur in infinite vacuum energy(electromagnetic vacuum energy), and was previously unknown to physics. So some of the scientific literature says this is a fascinating result.

However, the real world is three-dimensional, and the analysis must include those modes whose wave vectors are not perpendicular to the plate. Suppose there is a rectangular cubic cavity the plate length is a, the plate distance is d, and d«a, then the sum in the x and y directions is replaced by integral, and the formula is as follows:

$$E_c =$$
$$-\frac{\hbar c \alpha^2}{\pi^2} \left\{ \sum_n \int_0^\infty dk_x \int_0^\infty \sqrt{k_x^2 + k_y^2 + \frac{n^2\pi^2}{d^2}} \, dk_y - \right.$$
$$\left. \frac{d}{\pi} \int_0^\infty dk_x \int_0^\infty dk_y \int_0^\infty \sqrt{k_x^2 + k_y^2 + \frac{n^2\pi^2}{d^2}} \, dk_z \right\}$$
$$(33)$$

In this case, the third derivative is used in the Euler-Maclaurin summation formula, we obtained:

$$E_c = -\frac{\pi^2 \hbar c \alpha^2}{720 d^3} \qquad (34)$$

and then

$$F_c = \frac{\partial E_c}{\partial d} = -\frac{\pi^2 \hbar c \alpha^2}{240 d^4} \qquad (35)$$

This is the Casimir force formula; It can be seen that $E_c \propto a^2$ (the greater the force of the plate area), and $F \propto d^{-4}$ (the smaller the spacing, the greater the force). The reason for the former can be understood as the larger the plate area is, the more significant the difference between internal and external photon numbers is; the reason for the latter can be understood as the smaller d is, the smaller the allowable module between plates is (the fewer photons are), resulting in the larger force. Note the difference between Casimir force and Newton gravitation, where the law is $F \propto d^{-2}$ and the magnitude of the force is proportional to the product of the masses of the two plates($F \propto m^2$). But for Casimir force, F has nothing to do with the mass of the metal plate.

Since this is now a square conductor plate with area a^2, the pressure (force per unit area) is

$$P = \frac{F_c}{a^2} = -\frac{\pi^2 \hbar c}{240 d^4} \qquad (36)$$

When the dimension of F is dyne, the dimension of a is cm, and the dimension of d is μm, Equation (36) is

$$P = -\frac{0.013}{240 d^4} \text{ dyne/cm}^2 \qquad (37)$$

If d=1μm and the plate area is a^2=1cm^2, F_c=-1.3×10^{-2} dyne=-1.3×10^{-7} N, it is a very small force, approximately equivalent to the gravity of a water drop with a diameter of 0.5mm.The force is small, but may be considerable if d is greatly reduced (it must be noted that when d→0, F_c→∞.) In fact, if d=10nm, p=1atm; So in the nanoworld this force is not negligible, perhaps far more important than Newtonian gravity. In addition, when d=1μm, the Coulomb force between the two plates will be greater than the Casimir force (when the voltage between the two plates is 17mV). This number can give people an idea of the size of the Casimir force. The derivation of the formula assumes that the material is an ideal reflection at all frequencies, that is, the conductivity of the plate is infinite, so the actual material formula needs to be modified.

Casimir's formula is now part of the history of physics.But in the late 1940s, when Casimir told the famous W. Pauli that there was "attraction between two conducting plates," he dismissed it as"nonsense." But after Casimir insisted, Pauli finally accepted the result.

In physics, the Casimir effect (or Casimi force)may at first seem a bit strange—a pair of metal conducting plates (parallel to each other) in a vacuum can act as if they were attracted to each other, but not gravitation. This force is small, but it is much stronger than gravity; Its existence can be measured, but the measurable effect is required at very small distances (microns or even nanometers) between the plates, which is technically very difficult.

The quantized electromagnetic field is a quantum system with infinite number of harmonic oscillators. The ground state has zero vibration and corresponding ZPE, and the zero vibration of all modes is the vacuum fluctuation of the quantum electromagnetic field — although the mean value is zero, the mean square value is not zero. Therefore, quantum theory believes that vacuum has energy, and the total size is $\frac{1}{2}\sum_i \hbar\omega_i$, Since the degree of freedom i(i.e., vibrational modulus i) is infinite and the upper limit of ω is infinite, this vacuum energy is divergent and unobtainable. However, it is possible to calculate and measure the change in the vacuum energy by placing two parallel metal plates into an open cavity, which changes the boundary conditions of the field and thus the frequency of the harmonic oscillator, causing the energy of the vacuum state to change. Although ZPE is still divergent and cannot be observed after implantation, its energy difference before and after implantation can be calculated and observed. This is the Casimir energy, I'll call it E_c; The corresponding force acting on the metal plate, the Casimir force, is denoted as F_c. Now, E_c is equal to the difference between the ZPE in the vacuum between the plates and the ZPE in the absence of the plates:

$$E_c = \left[\sum \frac{1}{2}\hbar\omega_i\right]_{wp} - \left[\sum \frac{1}{2}\hbar\omega_i\right]_{np} \qquad (38)$$

This way we can get a clearer physical idea. In equation(38), wp is "with plates", np is "no plates".

But what is the meaning of negative sign? First, the plates is attracted to each other. Next, "Negative energy" can be understood as "the emptiness between the plates is more empty than the vacuum", which must produce inward force to bring the plates closer, Because of this, Lamoreaaux's measurements in 1997 were considered to "measure negative energy"; But the question is debated.

6. THEORETICAL RESEARCH PROGRESS

Casimir effect is a macroscopic quantum phenomenon deduced from quantum field theory, which cannot be understood from the perspective of classical physics. But this does not mean that classical Maxwell field theory (and its associated mathematical methods) are meaningless. Of course, the main analysis method is to rely on QFT and QED. Now some situation and progress of theoretical research are given.

Casimir's articles, the main two are hard to find (Proc.K.Ned. Akad. Wet, 1948, Vol. 51,793; J. Chim. Phys., 1949, Vol. 46, 407). Easily searchable is an article he co-authored with Polder entitled "The effect of delay on London-van der Waals forces"[1]. In this paper, it first analyze the interaction between a neutral atom and an ideal conducting plate, and then the interaction between two neutral atoms, using quantum electrodynamics (QED) to deal with the effect of delay on the interaction energy. This article does not cite the concept of ZPE.

In 1956, E. Lifshitz proposed his own theory (J.Exp. Theor, Phys., Vol.2, 73): using the fluctuation dissipation theorem, he derived general formulas for free energy and dispersion interaction. His Fluctuating electromagnetic field is a classical simulation of Casimir's theory. Lifshitz's method has since been used by several authors. In addition, he supported an experiment to study the attraction between dielectric materials (Sci. Am., July 1960, 47), which promoted scientific attention.

Lifschitz derived Casimir formula using van der Waals force only; Later R, Jaffe argued that Casimir forces need not be explained by vacuum fluctuations. van der Waals force is the force between two neutral spherical atoms at rest due to the instantaneous electric dipole moment (due to the instantaneous center difference between positive and negative charges). It should be zero at 0K, but it's not zero because of the zero

vibration. In the case of Casimir effect, the physical phenomenon may be caused by ZPE or van der Waals forces. In 1993, C.Sukenik et al.conducted experiments with a cavity in which the distance between plates could be adjusted at 0.5~8μm and a sodium atom beam passed through the cavity placed in a vacuum. Experiments show that it is consistent with quantum electrodynamics (QED) calculations and not with van der Waals forces.

In 2006, M, Bordag [27] used the path integral in quantum field theory (QFT) to give the Green function expression of E_c ,which is caused by the Casimir between plates being treated as a massless scalar field, actually combining classical field theory with QFT. In 2010, Qiu Weigang [28] pointed out that there are four types of boundary conditions for double plates:(D, D), (D, N), (N, D)and(N, N), where D represents Dirichlet boundary conditions of the first type and N represents Neumann boundary conditions of the second type. The negative energy (E_c <0) generated by the combined action of (D, D) and (N, N) is gravitational action; the positive energy(E_c >0) generated by the combined action of (D, N) and (N, D) is repulsion action. In 2007, Zeng Ran et al. [8] derived and calculated the Casimir force between plates of negatively refracted materials, and discussed the influence of dispersion relation of negatively refracted materials on Casimir effect.

In 2009, M.Bordag et al. [29] published 《Advanced in the Casimir Effect》 (745 pages) in Oxford University Press, which is a tour de force Study of on Casimir effect. The book is divided into three parts: Ⅰ. Physical and mathematical basis of ideal boundary Casimir effect; Ⅱ. Casimir force between entities; Ⅲ. Casimir force measurement and its applications in fundamental physics and nanotechnology. There are about 700 references at the end of the book, among which 5 papers written by Casimir are listed in the references for the convenience of readers. This book co-authored by four authors is the most advanced and fruitful book in theoretical research so far, which has a landmark significance.

In 2007, S. Lamoreaux [30] published a paper "Casimir forces: still surprising after 60 years". It pointed that between quantum fluctuations and forces have now pervades all areas of physics, and that experimenters and theorists have also found the Casimir force problem challenging, In this paper, so me applications related to fine structure constant, electronic structure, black hole theory are discussed. 2008 marks the 60th anniversary of the discovery of Casimir forces, and several other articles have highlighted its contributions to theoretical physics.

7. CASIMIR EFFECT CAUSES UNIQUE NEGATIVE ENERGY VACUUM AND SUPERLUMINAL PHENOMENA

Previous theoretical work has profoundly revealed the nature of Casimir effect causing quantum vacuum and leading to faster-than-light (superluminal) phenomenon. The uniqueness of these works requires a special discussion.

In 1990, K. Scharnhorst [31] from Germany and G. Barton from Britain published an article in the same journal, claiming to discover the phenomenon of faster-than-light speed in Casimir effect (Scharhorst, Phys.Lett, B236, 1990, 354; Barton, Phys. Lett., B237, 1990, 559). This was in the first half of 1990. In July of the same year, S.Ben-Menahem [32] from the United States published a paper entitled "Causality between dual conductor plates" in the same journal, commenting on the work of the aforementioned two men. These papers are high level, for example using quantum electrodynamics (QED) concepts and Feynman diagrams for analysis. As a result of Scharmhorst's work, the author concludes that the structure of vacuum is changed by placing two plates in the vacuum, so there are two kinds of vacuum; normal vacuum or free vacuum outside the plate, and negative energy vacuum between the plates. For electromagnetic wave propagation perpendicular to the plate, the speed of light in vacuum is not the same, and the variation ($\Delta c/c$) is about 1.6×10^{-60} d^{-4}, so when d=10^{-9}m, Δ c=10^{-24}c. Therefore, due to the double loop effect of quantum electrodynamics, Scharnhorst concluded that this would make the phase and group velocity of electromagnetic waves greater than the speed of light in vacuum.

Now that this Casimir effect has been experimentally demonstrated, we have to accept that the "two vacuums" statement is true and that it is logical that the speed of light inside and outside the plate may be different. Thus, it is the change in boundary conditions that affects the vacuum and thus the propagation speed of electromagnetic waves. In other words, the

propagation of light depends on the structure of the vacuum, which is the basic idea of quantum physics. It is due to the Casimir effect that we can distinguish between the following: ①normal vacua (also called free vacua); ② vacuum between the plates; The latter is characterized by vacuum energy density and can also be called negative energy vacua, which is the physical basis for faster-than-light phenomenon.

Scharnhorst first calculated the refractive index in the direction perpendicular to the board surface:

$$n_p = \sqrt{\varepsilon_{11}\mu_{11}} \tag{39}$$

Where, ε_{11} 、 μ_{11} is the permittivity tensor component and the permeability tensor component; The subscript p of n stands perpendicular. Eventually the export

$$n_p = 1 - \frac{11}{2^6 45^2} \frac{e^4}{(md)^4} \tag{40}$$

Where, d is the distance between two ideal conductive plates; m is mass, c Is the speed of light in normal vacuum (free vacuum), then

$$c = \left\{1 + \frac{11}{2^6 45^2} \frac{e^4}{(md)^4}\right\} c_0 \tag{41}$$

Where, c is the speed of light in the vertical direction of the plate surface under the condition of interplate vacuum. The difference between c and c_0 is due to the change in the vacuum structure, which is caused by placing two plates. The result is c> c_0, where c_0 =299792458m/s, and the c is greater than c_0, i.e., faster - than - light. Further calculation gives:

$$\frac{\Delta c}{c} = \frac{c - c_0}{c} \tag{42}$$

Take d=1μm, $\Delta c / c$ =1.6×10^{-36}, which is very small; But even this is at odds with special relativity (SR)—SR theory does not allow anything to exceed the speed of light, however small. Try reducing d again—for a 1nm gap (d=1nm), increment Δc =10^{-24} c. This number is also very small, but can be significant in some cases. In short, Scharhorst did not calculate "the speed of a photon traveling between two metal plates," but rather the speed of a wave traveling vertically between two plates, and found that the phase velocity was slightly higher than the speed of light (v_p >c). When the frequency is not high, the dispersion can be ignored and the group velocity is equal to the phase velocity, so the group velocity is slightly higher than the speed of light (v_g >c).

In 1993, G.Barton and K.Scharnhorst [33] reinterpreted the problem by calling two metal plates "parallel mirors". Paper title, or by "OED between parallel mirrors: light signals faster than c,or amplified by the vacuum"); The abstract of the paper states: "Due to the scattering of the quantized field, the light traveling vertically between two parallel double mirrors with a frequency of ω experiences a vacuum as a dispersive medium of refractive index n(0). Our earlier low-frequency results, representing n(0)<1, combine the Kramers-Kroning dispersion relationship with the classic Sommerfeld-Brillouin argument to declare either case: ①n(∞)<1 and c/n(∞)>c; ②The imaginary part of n is negative, and the vacuum between the mirrors is insufficient to respond to light detection as a normal passive medium. It is clear, therefore, that the authors are concerned with the properties of vacuum; They think that under the physical conditions and conditions of Casimir effect, the refractive index of vacuum is no longer equal to 1, but may be smaller than 1. This, of course, is still the QFT's view, as opposed to classical physics. In addition, it should be noted that Scharnhorst's "group velocity hyperluminal" has two conditions: one is the wave perpendicular to the plate; Second, the frequency is not too high(ω « m$_e$).

Why does the electromagnetic wave velocity ratio c between two metal plates depend on Casimir effect occur? Conceptually, considering the Maxwell electromagnetic field at zero absolute temperature between two parallel plate mirrors (distance d), the board is assumed to be an ideal conductor at any frequency. The outer boundary condition of the plate is E$_{11}$=0 and B$_\perp$ =0. if the field is quantized, the vacuum structure of the plate is different from that of the unbounded space. In particular, the square of the field component and the energy density differ— the latter being lower, as demonstrated by the Casimir effect.

It is well known that even without mirrors, the zero-point vibration of Dirac's electron/proton field profoundly changes the vacuum properties, which is what distinguishes QED from classical physics. For example, they introduce nonlinearity into Maxwell's equations, and light scattering occurs. These nonlinear combination mirrors alter the zero Maxwell field, resulting in light velocities between mirrors perpendicular to the mirrors that may exceed c; Between the two mirrors, with respect to unbounded space, the plane wave detection propagation is changed (inductive coupling from the Fermion of the detection field to the zero oscillation of the quantized Maxwell field). When $\omega \ll m_e$, the nonlinear correction of Maxwell equation can be concluded as Euler-Heisenberg effective Laplace quantity density:

$$\Delta L = \frac{1}{2^3 3^2 5 \pi^2} \frac{e^4}{m^4} \left\{ (\boldsymbol{E}^2 - \boldsymbol{B}^2) + 7 (\boldsymbol{E} \cdot \boldsymbol{B})^2 \right\} \quad (43)$$

The results show that for vertical propagation between mirrors, the effective refractive index becomes:

$$n = 1 + \Delta n \quad (44)$$

And

$$\Delta n = \frac{11 \pi^2}{2^3 3^4 5^2} \frac{e^4}{(md)^4} \quad (45)$$

The refractive index of propagation parallel to the mirror is still 1, the same as that of unbounded space.

There are now

$$\frac{1}{n} = \frac{1}{1 + \Delta n} \approx 1 - \Delta n \quad (46)$$

$$v_p = \frac{\omega}{k} = c \frac{1}{n} = c (1 - \Delta n) = c (1 + |\Delta n|) \quad (47)$$

Group velocity is (in case of no dispersion):

$$v_g = \frac{d\omega}{dk} = v_p = c (1 + |\Delta n|) \quad (48)$$

Δn is too small for real measurements; It's really just

$$|\Delta n| = \frac{\Delta c}{c} \quad (49)$$

Considering that n= $\sqrt{\varepsilon \mu}$, so

$$\Delta n = \frac{1}{2} (\Delta \varepsilon + \Delta \mu) \quad (50)$$

$\Delta \varepsilon$ and $\Delta \mu$ may be understood as the changes of permittivity and permeability with position.

In 1998, Scharnhorst [34] published his last paper on this topic. It is worth noting that he proposed the phrase "modified QED vacua", which is consistent with our discussion of the two vacuums in this section.

8. EXPERIMENTAL RESEARCH PROGRESS

Speaking of experiment, it is the only means of making people accept a new theory. Because Casimir forces are weak, experiments are difficult. The first person to do an experimental verification of theoretical expectations for the attraction of parallel plates was M.Sparnaay (Physica Amsterdam, 1958, Vol. 24,751), and although with a great deal of error (up to 100% uncertainty), it is widely cited. The experiment is still interesting today. First, it measures the Casimir force between the conductor plates. It uses springs and cleverly constructed capacitors—a change in force is a change in capacitance, which can be measured. This proves once again that experimental design in scientific research is a very innovative work. After 1973 various experiments were carried out. Since 1994, S.Lamoreaux began an experimental study of Casimir forces and worked to improve the accuracy, with experiments ranging from d=0.6 to 6μm, In fact, this was the beginning of the verification of Casimir forces with sufficient accuracy, which was published in 1997 [35], half a century after Casimir's paper was published. Lamoreaux measures the Casimir force between a gold-coated spherical lens and a conductor plate connected to a torsion balance. The Casimir force makes it torsion, and the measurement accuracy is 5%~10% at the distance of d=1μm, and the result is equivalent to E=(10-15)J. The earlier theory was finally well proved (though not by two plates but by one between a plate and a gold-plated surface), and in 1998, U.Mohideen and A.Roy [36] measured the Casimir force more accurately at d=0.1-

0.9μm, using aluminized plates and small spheres, the latter with a diameter of 200±4μm. Laser technology was used in the measurement, and the experimental results confirmed the Casimir theory with an accuracy of 1%. Knowing that Casimir himself did not die until 2000 (at the age of 91), and that he had reached an advanced age in 1997 and 1998, it must have been a mixed feeling to hear that the Casimir force had been accurately measured.

Mohideen's experiment is of great significance. His measurement result is: F_c =-(160~2)pN, that is, the absolute value of F_c, from 1.6×10^{-10} N to 2×10^{-12}N, are very small; This is between two aluminum surfaces. The force is so small that the difficulty of measuring it is conceivable; Moreover, the influence of skin depth and surface roughness cannot be ignored and must be reflected in the data correction. Fig. 2 is an example of this measurement (quoted from Klimchitskaya et al. [10], where d represents the distance between two aluminum surfaces, and the vertical coordinate F_c is in units of 10^{-12}N; the dotted line is the ideal metal surface, the actual line is the non-ideal metal surface.
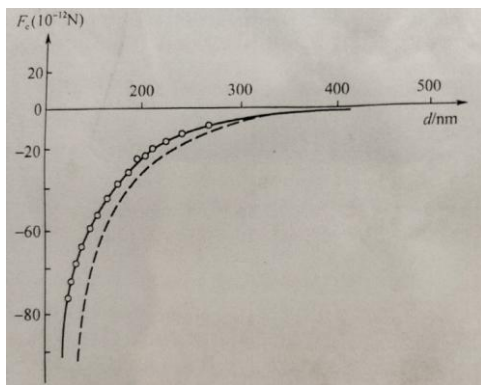

Fig. 2. Schematic diagram of Casimir force measurement results

Literature [37] is another example of measurement; There are many more articles of this kind, and it is impossible to describe in detail the relevant research work. G. Klimchitskaya of St. Petersburg published a long article "Casimir Forces between practical materials: experiments and theory" in 2009, with a total of 340 references at the end. It can be seen that in recent years, more and more in-depth and meticulous research. In addition, Chinese scientists have published theoretical work in this area, but no one seems to have carried out experiments, possibly because of the difficulty of doing experiments.

9. CONCLUSION

Casimir effect can also be regarded as a pillar of QED. It can be seen from the foregoing that the concept of ZPE is used in deriking Casimir force, so the experimental proof of Casimir force (F_c) is also the experimental proof of ZPE theory. This work later led to a great discussion on"whether vacuum really has energy", and in concept radiated to the recognition of virtual photons and negative energy. It can be said that it is "connected with the whole body"! The improvement and deepening of understanding of basic scientific problems will certainly lead to advances in applied science, for example, the Casimir effect has been proposed in nanotechnology to be considered.

The focus of this paper is to improve the understanding of the nature of quantum vacuum. In the past, to say that "vacuum is not empty" was already a criticism and subversion of classical physics. Now it seems doubly strange to say that there is a negative energy vacuum that is "empty" than the normal physical vacuum. But these theories are rigorously justified; Casimir effect can create an environment with refractive index less than 1(n<1) and lead to the appearance of superluminality, which is one of the representations of "quantum superluminality" [38]. These advances in basic science will certainly open up new fields of application, In short, it is not the Casimir structure that creates the quantum vacuum, but the structure that makes the quantum vacuum "emerge" in a clever way as a perceptible physical reality. This is truly a scientific achievement.

But much remains unclear. People ask, for example, is ZPE a physical reality or an auxiliary analytical tool? Is it an energy that can be extracted and applied in practice? Can we really get energy from a vacuum? There is a great deal of disagreement and debate about this. For example, although Lamoreaux's results are in line with ZPE's expectations, Jaffe argues that the Casimir effect does not provide a measure of ZPE, and therefore cannot measure energy in a vacuum. S.Catroll said that vacuum fluctuations are real and it is the Casimir effect that makes them manifest. In short, the scientific community is still divided on the Casimir effect.

The Casimir effect can be derived (explained) by classical physics? I do not agree with this statement, because there is no "(weak) attraction between parallel plates" in classical electrodynamics anyway; Otherwise, the great scientist Wolfgang Paul(1900-1958) would not have said at first (but later changed his mind) that Casimir's paper was nonsense. some theoretical derivations do not lead us to believe that "classical physics is valid and therefore quantum physics is not involved", we firmly believe that quantum theory is the most convincing way to understand Casimir effect.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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