Gravitational-wave detection by dispersion force modulation in nanoscale parametric amplifiers

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Quantum Mechanical Actuation of Microelectromechanical Systems by the Casimir Force

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The Casimir force is the attraction between uncharged metallic surfaces as a result of quantum mechanical vacuum fluctuations of the electromagnetic field. We demonstrate the Casimir effect in microelectromechanical systems using a micromachined torsional device. Attraction between a polysilicon plate and a spherical metallic surface results in a torque that rotates the plate about two thin torsional rods. The dependence of the rotation angle on the separation between the surfaces is in agreement with calculations of the Casimir force. Our results show that quantum electrodynamical effects play a significant role in such microelectromechanical systems when the separation between components is in the nanometer range.

A Tiny Force Of Nature Is Stronger Than Thought

By KENNETH CHANG

“A new experiment involving a tiny ball and seesaw has demonstrated that what was thought to be a mere curiosity of quantum mechanics could yield a force powerful enough to be harnessed for use in future microscopic devices,” said Dr. Federico Capasso, vice president of physics research at Bell Labs in Murray Hill, N.J., and senior author of a report that will appear in the journal Science.

Under the rules of quantum mechanics, a vacuum generates an attractive force between two metallic surfaces. Empty space is never completely empty, but instead burbles with “virtual particles” that wink into existence and then vanish before they can be detected. Though ephemeral, virtual particles still exert pressure by bouncing off objects during

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The Casimir effect, a curious consequence of quantum theory, may yet have practical applications

Can something come of nothing? Philosophers debated that question for millennia before physics came up with the answer—and that answer is yes. For quantum theory has shown that a vacuum (ie, nothing) only appears to be empty space. Actually, it is full of virtual particles of matter and their anti-matter equivalents, which, in obedience to Werner Heisenberg’s uncertainty principle, flit in and out of existence so fast that they cannot usually be seen.

However, in 1948, a Dutch physicist called Hendrik Casimir realised that in certain circumstances these particles would create an effect detectable in the macroscopic world that people inhabit. He imagined two metal plates so close together that the distance between them was comparable with the wavelengths of the virtual particles. (Another consequence of quantum theory is that all particles are simultaneously waves.) In these circumstances, he realised, the plates would be pushed together. That is because only particles with a wavelength smaller than the gap between the plates could appear in that gap, whereas particles of any wavelength could appear on the other sides of the plates. There would thus be more particles pushing in than pushing out, and the plates would clash together like a pair of tiny cymbals.

A neat idea. And in 1996, it was shown experimentally to be true. But so what? The answer is that now things in the computing industry have become so small that the Casimir force is starting to affect them. Computer engineers talk of “stiction”—the phenomenon of microscopic components sticking together—and spend a lot of time trying to figure out ways to avoid it. The Casimir effect is not the only cause of stiction, but it is an important one.
KNOWLEDGE ABOUT DISPERSION FORCES has already been transferred into novel and unique products:

- Biological systems
- Synthetic adhesives

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THE GENERAL THEORY OF MOLECULAR FORCES.

By F. London (Paris).

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Following Van der Waals, we have learnt to think of the molecules as centres of forces and to consider these so-called Molecular Forces as the common cause for various phenomena: The deviations of the gas equation from that of an ideal gas, which, as one knows, indicate the identity of the molecular forces in the liquid with those in the gaseous state; the phenomena of capillarity and of adsorption; the sublimation heat of molecular lattices; certain effects of broadening of spectral lines, etc. It has already been possible roughly to determine these forces in a fairly consistent quantitative way, using their measurable effects as basis.

(Communicated at the meeting of May 29, 1948.)

For the force per cm² we find

\[
F = \hbar c \frac{\pi^2}{240} \frac{1}{a^4} = 0.013 \frac{1}{a^4} \text{ dyne/cm}^2
\]

where \( a_\mu \) is the distance measured in microns.

We are thus led to the following conclusions. There exists an attractive force between two metal plates which is independent of the material of the plates as long as the distance is so large that for wave lengths comparable with that distance the penetration depth is small compared with the distance. This force may be interpreted as a zero point pressure of electromagnetic waves.

Although the effect is small, an experimental confirmation seems not unfeasable and might be of a certain interest.
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\[ I_{\text{Lif}}(s) \equiv \int_1^\infty dp \, p^2 \int_0^\infty dx \, x^3 \left( \left[ \frac{1}{X e^{xp} - 1} \right] + \left[ \frac{1}{Y e^{xp} - 1} \right] \right) \]

\[ X \equiv \left( \frac{S + \epsilon p}{S - \epsilon p} \right)^2, \quad Y \equiv \left( \frac{S + p}{S - p} \right)^2, \quad S^2 \equiv p^2 - 1 + \epsilon \]

\[ \epsilon = \epsilon(i \xi) \]

\[ F_{\text{Cas}}(s) = -\frac{\hbar \, c}{32 \pi^2 s^4} I_{\text{Lif}}(s) \]
\[ ds^2 = c^2 \, dt^2 - (1 + h_{11}) \, dx^2 - (1 - h_{11}) \, dy^2 - 2h_{12} \, dx \, dy - dz^2 \]

\[ \frac{dr}{dt} = \frac{c}{n(\theta, \phi)} \]

\[ n(\theta, \phi) \approx 1 + \frac{1}{2} (h_{11} \cos 2\phi + h_{12} \sin 2\phi) \sin^2 \theta \]

\[ P_{\text{Cas}}(s) \approx \frac{\pi^2}{240} \frac{\hbar c}{s^4} \frac{1}{\sqrt{\epsilon_3}} \]

\[ P_{\text{Cas}}(s, h_{+}^{\text{TT}}; t) \approx \frac{\pi^2}{240} \frac{\hbar c}{s^4} \left( 1 - \frac{h_{+}^{\text{TT}}}{4} \cos \omega_{\text{GW}} t \right) \]

\[ \Delta P_{\text{Cas, GW}} \sim \frac{\pi^2}{240} \left( \frac{\hbar c}{s^4} \right) \left( \frac{GM}{c^4} \right) \frac{l_0^2 \Omega^2}{r} \propto \left( \frac{L_{*}}{s} \right)^2 \left( \frac{l_0}{s} \right)^2 \]

\[ \Delta P_{\text{Cas, GW}}(s = 10 \text{ nm}, h_{+}^{\text{TT}} = 10^{-20}) \approx 3.25 \times 10^4 \text{ yN} \]

M. J. Biercuk, Nature Nanotech. 5 (2010) 646 \sim 170 \text{ yN}
The Theory of Molecular Attractive Forces between Solids

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(Submitted to JETP editor September 3, 1954)

A macroscopic theory is developed for the interaction of bodies whose surfaces are brought within a small distance of one another. The interaction is considered to come about through the medium of the fluctuating electromagnetic field. The limiting cases of separations small and large compared with the wavelengths of the absorption bands of the solid are studied. Upon going to the limiting case of rarefied media, the van der Waals forces of interaction between individual atoms are obtained. The effect of temperature on the interaction of the bodies is considered.
\( \mathcal{E}_{\text{Cas}} = \frac{1}{V} \sum_{k, \lambda} \frac{1}{2} \hbar \omega_k \rightarrow \frac{2}{8\pi^3} \int d^3 k \frac{1}{2} \hbar \omega_k = \frac{4\pi}{8\pi^3} \int dk k^2 \frac{1}{2} \hbar \omega_k = \frac{\hbar}{2\pi^2 c^3} \int_{\omega_{\text{min}}}^{\omega_{\text{max}}} d\omega \omega^3 \)

\( \lambda_{\text{max}} = 2s \ (\omega_{\text{min}} = \pi c/s) \)

\( \mathcal{E}_{\text{Cas}} \rightarrow +\infty - \frac{\hbar}{8\pi^2 c^3} \omega_{\text{min}}^4 \sim +\infty - \frac{\pi^2 \hbar c}{8s^4} \)

\( E_{\text{Cas}} = \mathcal{E}_{\text{Cas}}(As) = +\infty - \hbar c \pi^2 A/(8s^3) \)

\( \mathcal{P}_{\text{Cas}} = -\left(1/\lambda\right) \left(\partial E_{\text{Cas}}/\partial s\right) = -\hbar c \delta / s^4 \quad \delta = \pi^2 / 240 \)

E. A. Power, *Introductory Quantum Electrodynamics*
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\[ F_{\text{Cas}} = \frac{B}{d^4} \]

\[ F_{\text{Cas}} = \frac{A}{d^3} \]
“The force between molecules”
“As we go down in size, there are a number of interesting problems that arise. All things do not simply scale down in proportion. There is the problem that materials stick together by the molecular (Van der Waals) attractions. It would be like this: After you have made a part and you unscrew the nut from a bolt, it isn't going to fall down because the gravity isn't appreciable; it would even be hard to get it off the bolt. It would be like those old movies of a man with his hands full of molasses, trying to get rid of a glass of water. There will be several problems of this nature that we will have to be ready to design for.”

There's plenty of room at the bottom
Richard P. Feynman, (29 December 1959)
The Anharmonic Casimir Oscillator (ACO)—The Casimir Effect in a Model Microelectromechanical System

F. Michael Serry, Dirk Walliser, and G. Jordan Maclay, Member, IEEE

Abstract—The sizes of and the separations between the components in some MEMS are already in the sub-micrometer regime [1], [2]. Further miniaturization is carrying the MEMS technology into a domain where some quantum mechanical effects, hitherto neglected, will need to be taken into account. When separations between objects are small enough, certain quantum effects become manifestly significant even if the masses of the objects are too large by quantum standards. The Casimir effect, for example, is the attractive pressure between two flat parallel plates of solids that arises from quantum fluctuations in the ground state of the electromagnetic field [3]–[5]. The magnitude of this pressure varies as the inverse fourth power of the separation between the plates. At a 20 nm separation between two metallic plates, the attraction is approximately 0.08 atmosphere. If one or both plates are nonconducting, the pressure is smaller, roughly by an order of magnitude. As an idealized MEMS component that takes account of the Casimir effect, the Anharmonic Casimir Oscillator (ACO) is introduced and shown to be a bi-stable system for certain values of the dimensionless parameter, $C$, which characterizes the system. The phenomenon of “stiction” in MEMS is then explained as

![Graph showing the minimum feature size (micrometers) vs. (projected) year of production.](image)

Fig. 1. Reduction of IC feature size. The minimum feature size on IC’s has been reduced by a factor of 2 approximately every six years. (Source: Chenci-ning Hu, “Mosfet scaling in the next decade and beyond,” Semiconductor International, vol. 17, no. 6, pp. 105–114, June 1994.)
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Fig. 2. Casimir, electrostatic, and gravitation pressures. A comparison of the attractive pressures due to the Casimir effect and applied electrostatic voltage (V) between two flat parallel plates of conductors in vacuum. Also shown are the gravitational pressure on 2-μm-thick (dashed line A) and 10-μm-thick (dashed line B) silicon membranes.

Fig. 3. The Anharmonic Casimir oscillator. Due to the Casimir effect, the moveable flat plate on the left, at δ < 1, is attracted to the stationary flat surface parallel to it on the right. The wall on the left is far from the movable plate and the linear restoring force due to the spring is zero at δ = 0.

Fig. 4. The normalized potential energy per unit area of the parallel plates. C = 0 corresponds to the absence of the Casimir effect; this reduces the system to a simple harmonic oscillator. For C < C_c0 (= 0.0819), the potential energy curve displays a pair of local extrema, corresponding to a stable and an unstable equilibrium state of the system. At C = C_c0, there is an inflection point at δ = 0.2. Finally, for C > C_c0, no local extrema exist.

\[ P(\delta) = P_k(\delta) + P_C(\delta) = -k w_0 \delta + \frac{3n}{w_0^2(1-\delta)^4}. \]
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A Dynamic Method for Measuring the van der Waals Forces between Macroscopic Bodies

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(Received 27 December 1971)

A new method for measuring the van der Waals forces between macroscopic bodies is described. In contrast to previous static methods we developed a new dynamic technique with a considerably higher reproducibility, sensitivity, and accuracy. With this experimental setup the van der Waals force between various specimens has been determined. In this paper we present the results on borosilicate glass at distances between 0.08 and 1.2 µ which are in good agreement with theory.
Influence of optical absorption on the Van der Waals interaction between solids

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(Received 22 January 1979)

The Van der Waals forces between a variety of macroscopic bodies have been measured with high accuracy by using a new dynamic method. Between samples of crystalline quartz and borosilicate glass separated by a distance $d$, the most important contribution to the Van der Waals forces was found to vary as $d^{-4}$ in good agreement with theory. For two silicon samples, however, and for the sample combination borosilicate-glass–silicon, the Van der Waals forces vary as $d^{-4}$ only for large sample separations ($d > 0.25$ μm). For smaller distances a marked deviation occurs which is not yet understood. Generation of free carriers by the illumination of the silicon samples with white light causes an increase of the Van der Waals force at large distances in qualitative agreement with an order-of-magnitude estimate.
Enrico Fermi: “The Ultimate Accelerator” (1954)
THE ATOMIC ACCELERATOR

by

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To anyone who has carried out experiments in physics with a large modern accelerator there always comes a moment when he wishes that a powerful spatial compression of his equipment could take place. If only the very large and massive pieces could fit into a small room! Physics
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\[ U_{\text{vdW,Lif}} = -\frac{\hbar S}{16\pi^2 s^2} \int_0^{+\infty} \frac{\tilde{\epsilon}_c(i\omega_I) - 1}{\tilde{\epsilon}_c(i\omega_I) + 1} \frac{\tilde{\epsilon}_{\text{OW}}(i\omega_I) - 1}{\tilde{\epsilon}_{\text{OW}}(i\omega_I) + 1} d\omega_I \]

\[ F_{\text{vdW,Lif}} = -\frac{S}{8\pi^2 s^3} \hbar I_{\text{Lif}} \]

\[ \epsilon_{I,G}(i\omega_I) = \bar{\epsilon}_{I,G} \delta(\omega_I - \omega_0) \quad \bar{\epsilon}_{I,G} = \int_0^{\infty} \epsilon_{I,G}(i\omega_I) \delta\omega_I \]

\[ F_{\text{vdW,z}} = \pm \frac{1}{32\sqrt{\pi}} \frac{R}{s^2} \frac{(\hbar \bar{\epsilon}_{I,G})^2}{(\pi \hbar \omega_0 + \hbar \bar{\epsilon}_{I,G})^{3/2}} \sqrt{\hbar \omega_0} \]

\[ \Delta F_{\text{vdW,z}} \simeq \pm \frac{1}{2} \frac{F_{\text{vdW,z}}(0)}{\pi \hbar \omega_0 + \hbar \bar{\epsilon}_{I,G}} \left[ \left(4\pi \hbar \omega_0 + \hbar \bar{\epsilon}_{I,G}\right) \frac{\Delta(\hbar \bar{\epsilon}_{I,G})}{\hbar \bar{\epsilon}_{I,G}} + \left(-2\pi \hbar \omega_0 + \hbar \bar{\epsilon}_{I,G}\right) \frac{\Delta(\hbar \omega_0)}{\hbar \omega_0} \right] \]

\[ v_{\text{eject}} = \sqrt{\frac{2}{m_{\text{core}}}} \left[ \Delta F_{\text{vdW,z}}(n - 1) - F_{\text{OFF},z}^{\text{OFF}} \right] L_{\text{core}}. \]
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Dr Fabrizio Pinto, Co-Director
Prof and Vice President Dr Ali Al-Kamli, Co-Director
2. – Sull’elettrostatica di un campo gravitazionale uniforme, ecc.

For the introduction to this paper see No. 1.

2.

SULL’ELETTROSTATICA DI UN CAMPO GRAVITAZIONALE UNIFORME E SUL PESO DELLE MASSE ELETTROMAGNETICHE


INTRODUZIONE.

Fine di questo scritto è la ricerca dell’alterazione prodotta da un campo gravitazionale uniforme sui fenomeni elettrostatici che hanno luogo in esso fatta sulle basi della teoria generale della relatività. Stabilita l’equazione differenziale che lega il potenziale elettrico alla densità delle cariche, e che corrisponde all’equazione di Poisson dell’elettrostatica classica, si riesce ad integrarla nel caso almeno che il campo di gravitazione sia sufficientemente poco intenso, ed il campo della gravitazione terrestre soddisfa largamente a tale condizione, trovando così le correzioni da apportarsi alla legge di Coulomb per la presenza del campo di gravità.

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Resolution of a paradox in classical electrodynamics

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It is an early result of electrostatics in curved space that the gravitational mass of a charge distribution changes by an amount equal to $U_0/c^2$, where $U_0$ is the internal electrostatic potential energy and $c$ is the speed of light, if the system is supported at rest by external forces. This fact, independently rediscovered in recent years in the case of a simple dipole, confirms a very reasonable expectation grounded in the mass-energy equivalence equation. However, it is an unsolved paradox of classical electrodynamics that the renormalized mass of an accelerated dipole calculated from the self-forces due to the distortion of the Coulomb field differs in general from that expected from the energy correction, $U_0/c^2$, unless the acceleration is torsional to the orientation of the dipole. Here we show that this apparent paradox disappears for any dipole orientation if the self-force is evaluated by means of Whittaker’s exact solution for the field of the single charge in a homogeneous gravitational field described in the Rindler metric. The discussion is supported by computer algebra results, diagrams of the electric fields distorted by gravitation, and a brief analysis of the prospects for realistic experimentation. The gravitational correction to dipole-dipole interactions is also discussed.

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PACS numbers: 04.20.–q, 03.30.+p, 04.40.—b, 04.80.Cc
Engines Powered by the Forces Between Atoms

By manipulating van der Waals forces, it may be possible to create novel types of friction-free nanomachines, propulsive systems, and energy storage devices.

Fabrizio Pinto

Why does the world stick together, rather than falling apart?

Isaac Newton grappled with this question in the preface to his Philosophiae Naturalis Principia Mathematica, first published in 1687.

For him, the forces that hold objects together are the result of interatomic forces—forces that are transmitted by the exchange of quantum mechanical particles, which describes the behavior of particles on the atomic scale. The key to this theory of interatomic forces is that any atom instantaneously generates what is called an electric dipole—after all, any atom has a positive charge and a negative charge, which is the result of the electron cloud surrounding the nucleus. The interaction of these two charges produces a force between the two atoms, which is called the van der Waals force.

However, the strength of the van der Waals force depends on the distance between the atoms, and as the distance between the atoms increases, the force decreases rapidly. This means that the van der Waals force is only effective over very short distances, typically on the order of a few nanometers. As a result, the van der Waals force is not strong enough to hold objects together over long distances, which is why the world falls apart.

But there is another way to think about the van der Waals force. Instead of thinking of it as a force that holds objects together, we can think of it as a force that holds objects apart. This is because the van der Waals force is actually a repulsive force, which means that it pushes objects away from each other. This is why the world falls apart.

So, the question is: how do we use the van der Waals force to create nanomachines that can move without friction? The answer is: by manipulating the van der Waals force.

One way to do this is by using carbon nanotubes. Carbon nanotubes are extremely thin tubes made of carbon atoms, which are only a few nanometers in diameter. They are very flexible and can be used to create nanomachines that can move without friction.

Another way to use the van der Waals force is by creating propulsive systems. Propulsive systems are nanomachines that can move by using the van der Waals force to push objects away from each other. This is similar to how a boat can move by pushing water away from the back of the boat. By using the van der Waals force, we can create propulsive systems that can move without friction.

Finally, the van der Waals force can also be used to create energy storage devices. Energy storage devices are nanomachines that can store energy and release it when needed. By using the van der Waals force, we can create energy storage devices that are small enough to be used in everyday objects, such as batteries or solar panels.

In conclusion, the van der Waals force is a powerful force that can be used to create novel types of nanomachines, propulsive systems, and energy storage devices. By understanding and manipulating the van der Waals force, we can create new technologies that can change the world.