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

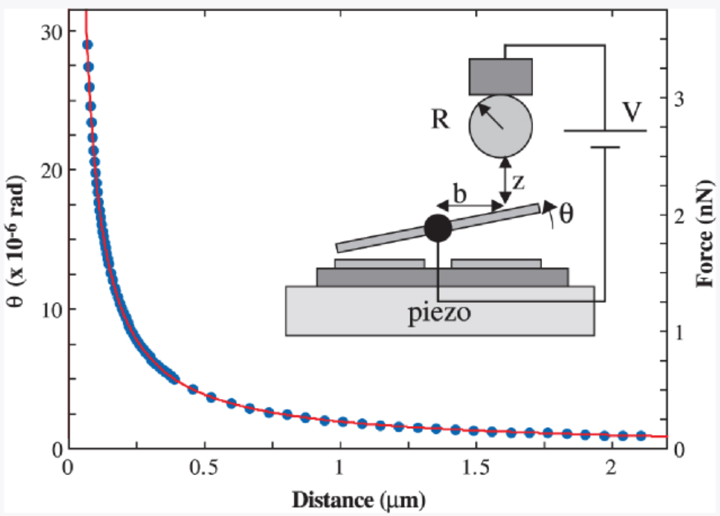
Dr. Fabrizio Pinto
Laboratory for Quantum Vacuum Applications,
Department of Physics, Faculty of Science, Jazan University - 9 September 2015

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

Quantum Mechanical Actuation of Microelectromechanical Systems by the Casimir Force

H. B. Chan, V. A. Aksyuk, R. N. Kleiman, D. J. Bishop, Federico Capasso*

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.



tiny and its presence was not verified until 1996 when Dr. Steve K. Lamo-

A quantum mechanical effect might have real-world utility.

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.

"This, we think, is a very interesting new direction to see how we can use quantum mechanical effects to actually make mechanical 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 pres-

... the thin

one 500-thousandth of an inch of each other, the Casimir Effect would generate a pressure of about 14 pounds a square inch — the air pressure of the atmosphere at sea level.

"That's a big number," Dr. Capasso said. "It's something that makes you think."

Dr. Capasso and his colleagues at Bell Labs, part of Lucent Technologies, essentially reproduced Dr. Lamoreaux's experiment on a microscopic scale. Instead of Dr. Lamoreaux's two coin-sized plates, the Bell Labs group used a tiny square of gold-plated silicon, about one-fiftieth of an inch on a side and mounted like a seesaw, and an even tinier sphere, which was also gold-plated.

As the sphere was lowered toward one side of the silicon seesaw, the Casimir Effect caused the seesaw to twist up slightly.

"Conceptually, the experiments are pretty much the same," Dr. Lamoreaux, now at the Los Alamos National Laboratory, said, comparing his work with that of the Bell Labs researchers. "It's almost exactly the same, with the exception of

Economist.com **SCIENCE & TECHNOLOGY**

The Casimir effect

Much ado about nothing

May 22nd 2008
From The Economist print edition

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.

Alamy

Virtual percussion

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.

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KNOWLEDGE ABOUT DISPERSION FORCES
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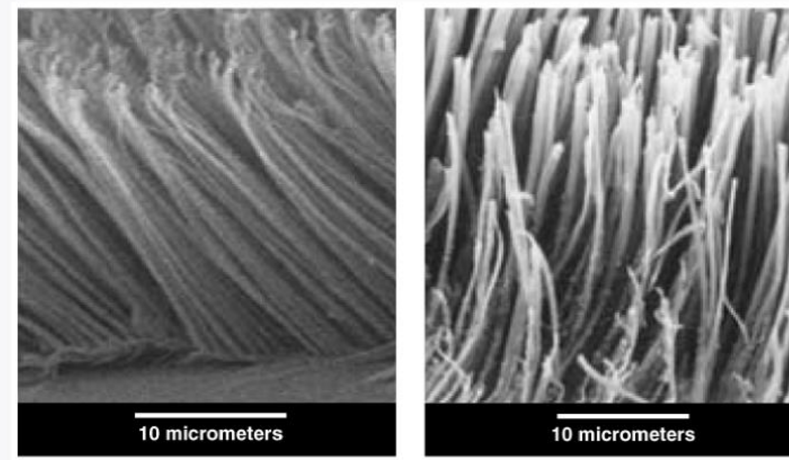

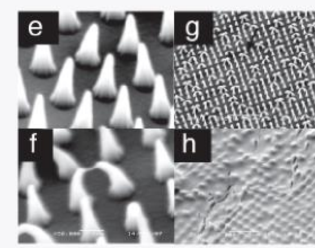

biological systems → **synthetic adhesives**

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TAUP 2015 | Centro Congressi Unione Industriale Torino | 9 September 2015 | GWs and Gravity

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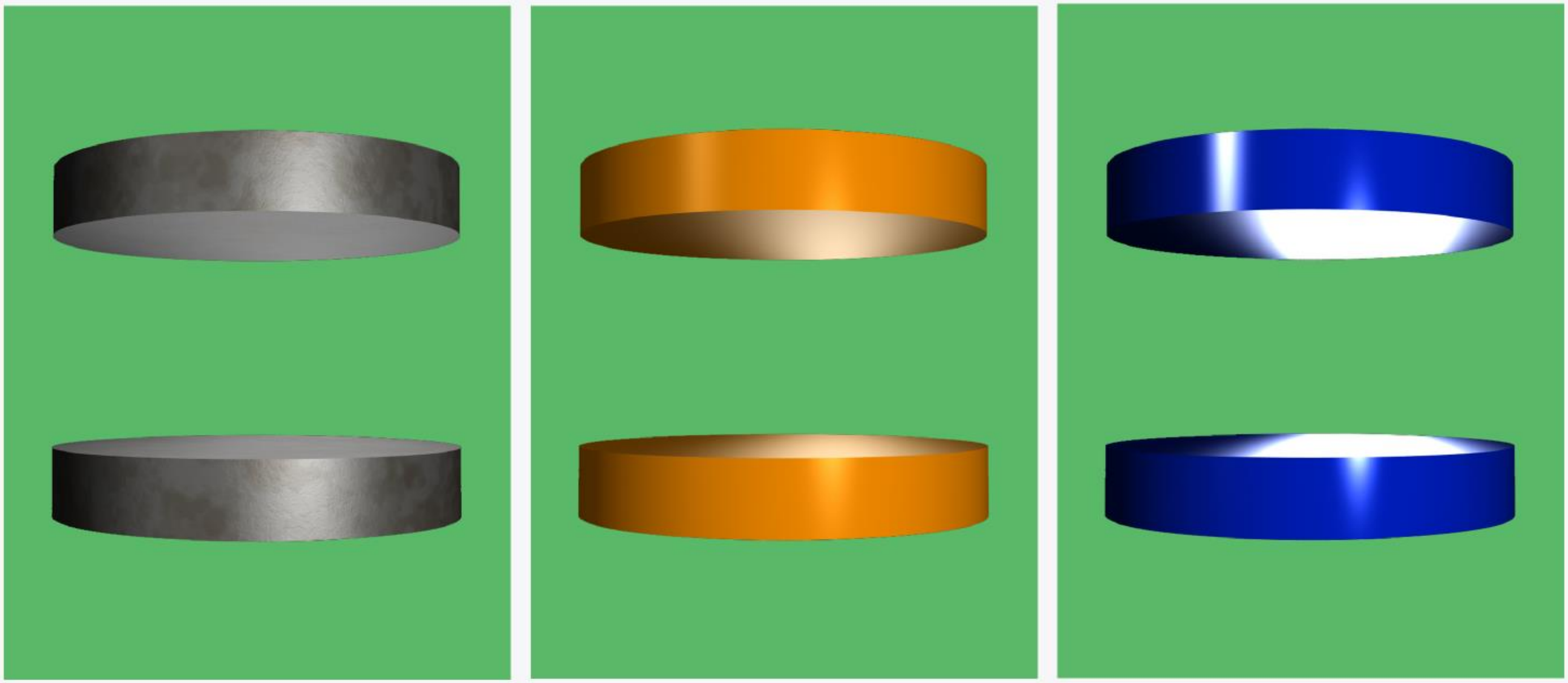

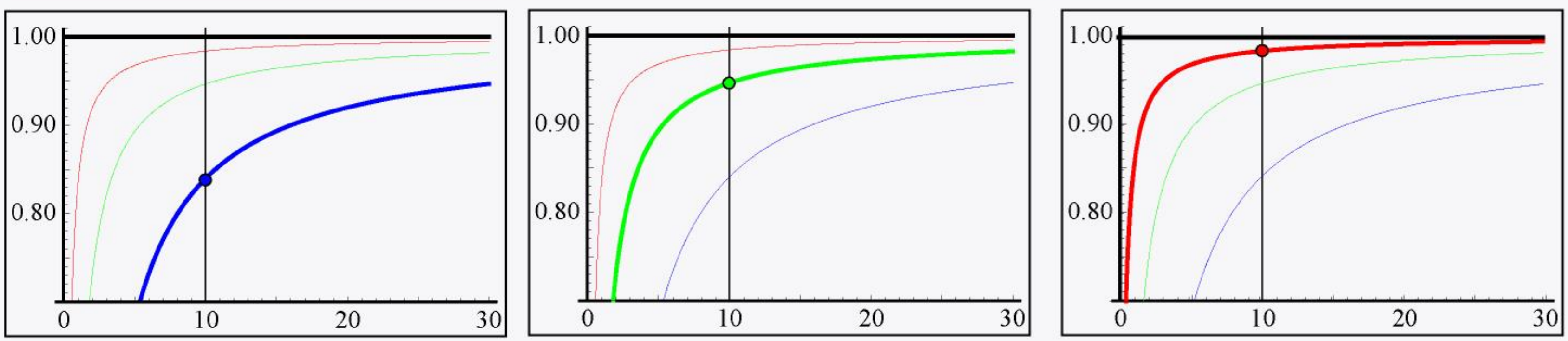

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THE GENERAL THEORY OF MOLECULAR FORCES.

BY F. LONDON (*Paris*).

Received 31st July, 1936.

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.

Mathematics. — *On the attraction between two perfectly conducting plates.* By H. B. G. CASIMIR.

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

For the force per cm^2 we find

$$F = \hbar c \frac{\pi^2}{240} \frac{1}{a^4} = 0{,}013 \frac{1}{a_\mu^4} \text{ dyne/cm}^2$$

where a_μ 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.

$$I_{\mathrm{Lif}}(s) \equiv \int_1^\infty dp\, p^2 \int_0^\infty dx\, x^3 \left(\left[\frac{1}{X e^{xp} - 1} \right] + \left[\frac{1}{Y e^{xp} - 1} \right] \right)$$

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

$$\epsilon = \epsilon(i\xi)$$

$$F_{\mathrm{Cas}}(s) = -\frac{\hbar c}{32 \pi^2 s^4} I_{\mathrm{Lif}}(s)$$

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$$ds^2 = c^2dt^2 - (1+h_{11})dx^2 - (1-h_{11})dy^2 - 2h_{12}\,dx\,dy - dz^2$$

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

$$n(\theta,\phi) \simeq 1 + \tfrac{1}{2}(h_{11}\cos 2\phi + h_{12}\sin 2\phi)\sin^2\theta$$

$$P_{\mathrm{Cas}}(s) \approx \frac{\pi^2}{240}\frac{\hbar c}{s^4}\frac{1}{\sqrt{\tilde{\epsilon}_3}}$$

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

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

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

M. J. Biercuk, *Nature Nanotech.* **5** (2010) 646 $\sim$ 170 yN

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SOVIET PHYSICS VOLUME 2, NUMBER 1 JANUARY, 1956

The Theory of Molecular Attractive Forces between Solids

E. M. LIFSHITZ
Institute for Physical Problems, Academy of Sciences, USSR

(Submitted to JETP editor September 3, 1954)
J. Exper. Theoret. Phys. USSR **29**, 94-110 (1955)

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.

$$\mathcal{E}_{\mathrm{Cas}} = \frac{1}{V}\sum_{\mathbf{k},\lambda}\frac{1}{2}\hbar\omega_k \to \frac{2}{8\pi^3}\int d^3k\frac{1}{2}\hbar\omega_k = \frac{4\pi}{8\pi^3}\int dk k^2\frac{1}{2}\hbar\omega_k = \frac{\hbar}{2\pi^2c^3}\int_{\omega_{\mathrm{min}}}^{\omega_{\mathrm{max}}} d\omega\omega^3$$

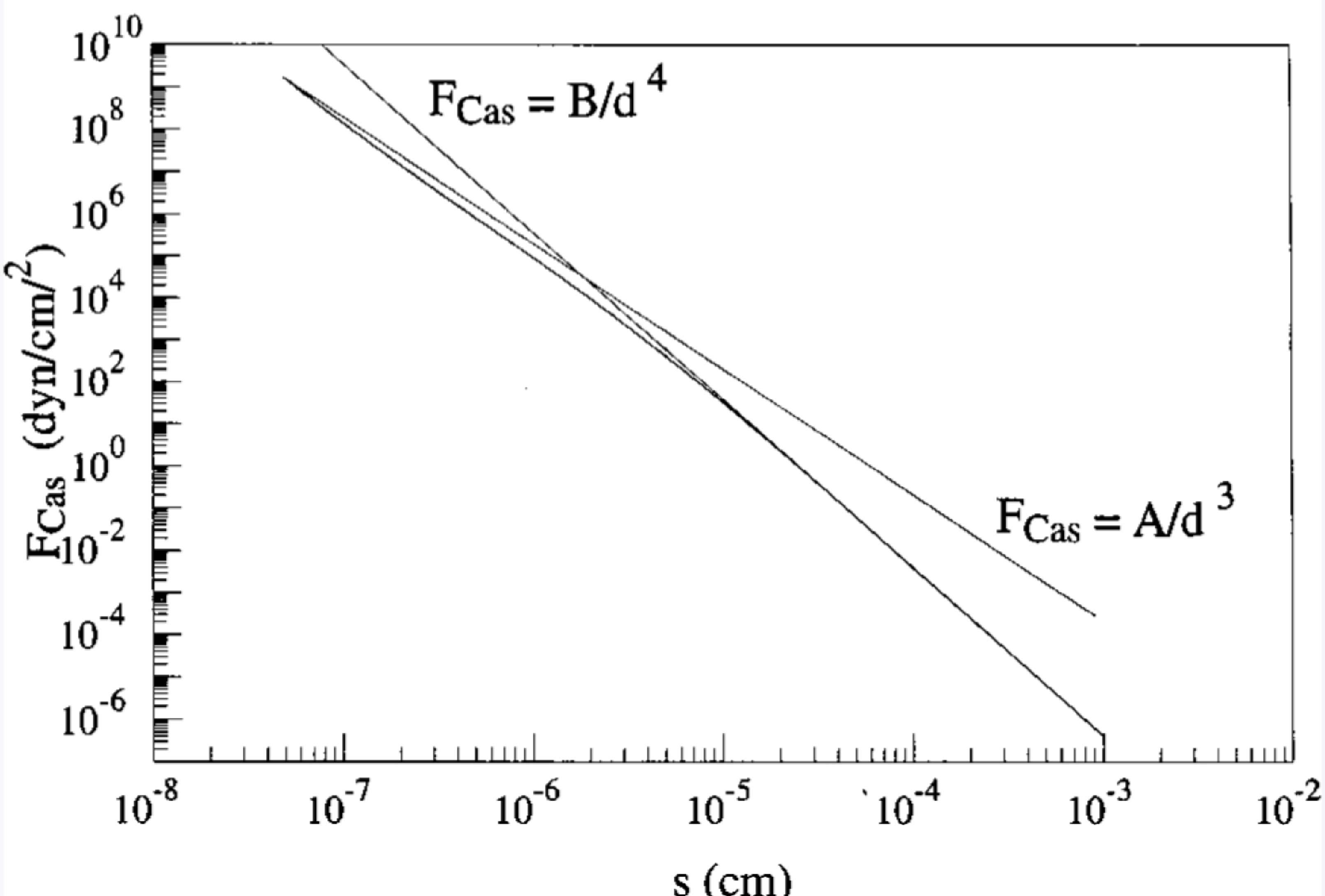
$$\lambda_{\mathrm{max}} = 2s \ (\omega_{\mathrm{min}} = \pi c/s)$$

$$\mathcal{E}_{Cas} \to +\infty - \frac{\hbar}{8\pi^2c^3}\omega_{min}^4 \sim +\infty - \frac{\pi^2\hbar c}{8s^4}$$

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

$$\mathcal{P}_{\mathrm{Cas}} = -(1/A)(\partial E_{\mathrm{Cas}}/\partial s) = -\hbar c\delta/s^4 \qquad \delta = \pi^2/240$$

E. A. Power, *Introductory Quantum Electrodynamics*



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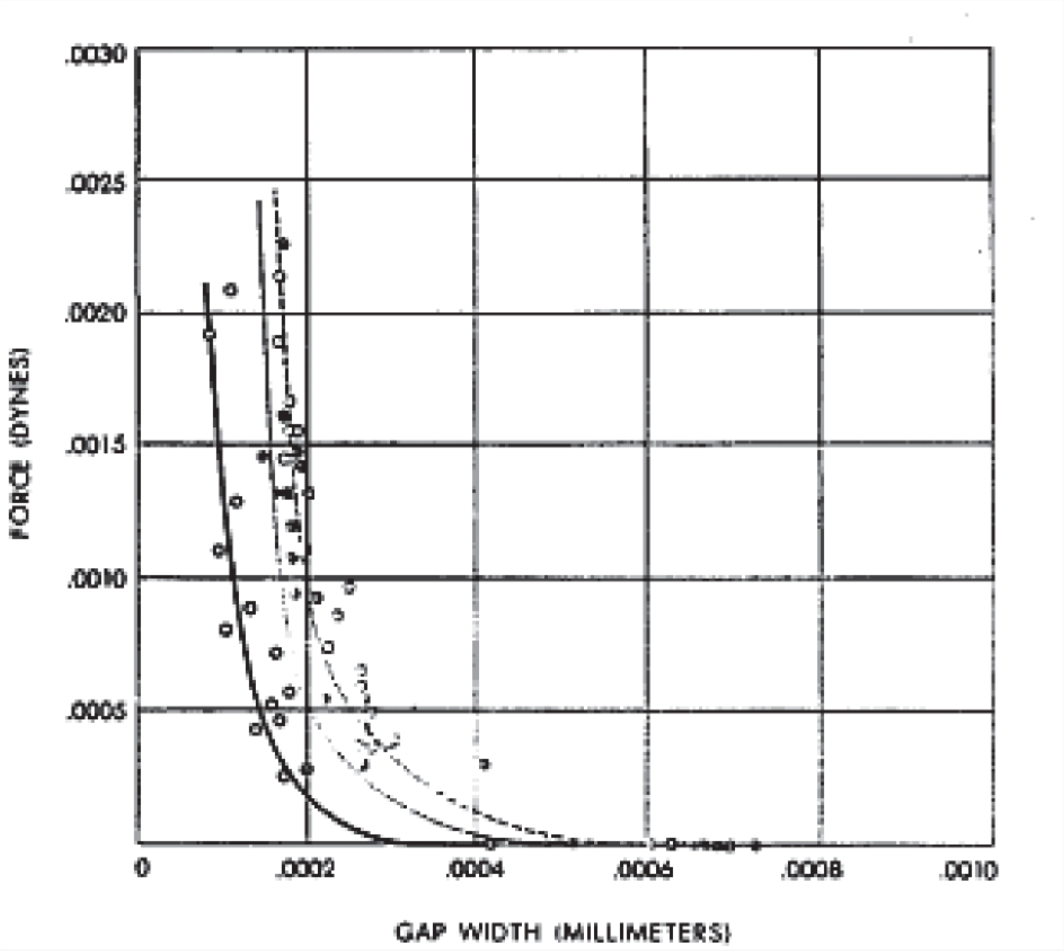

"The force between molecules"

Boris V. Derjaguin, *Scientific American*, **203**, 1, 47-53 (1960)

"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)

JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, VOL. 4, NO. 4, DECEMBER 1995 193

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].[1] The magnitude of this pressure varies as the inverse fourth power of the separation between the plates.[2] 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**

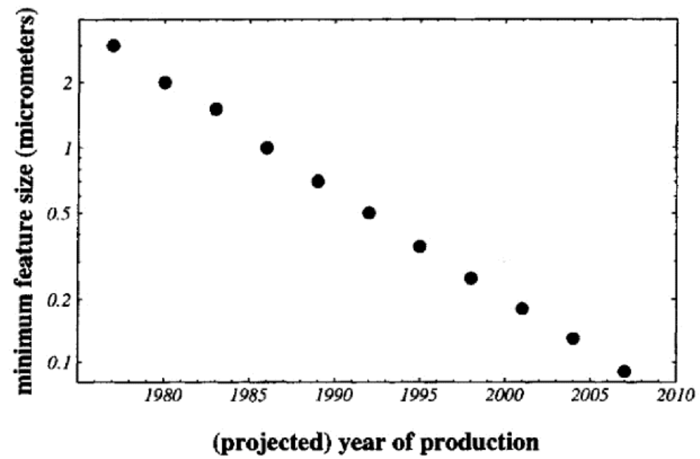

Fig. 1. Reduction of IC feature size. The minimum feature size on IC's has been reduced by a factor of 2 approximately every six years. (Source: Chenming Hu, "Mosfet scaling in the next decade and beyond," *Semiconductor International*, vol. 17, no. 6, pp. 105–114, June 1994.)

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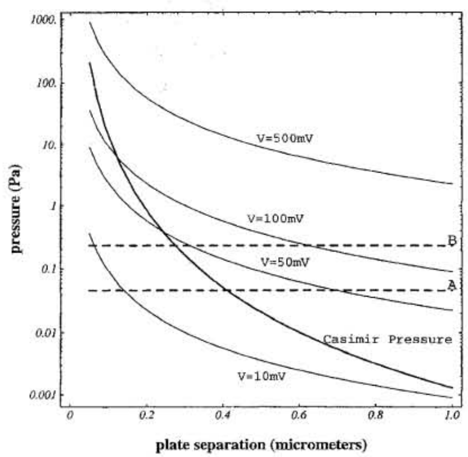

Fig. 2. Casmir, electrostatic, and gravitation pressures. A comparison of the attractive pressures due to the Casimir effect and applied electrostatic voltage (V) between two flat parallel plates of conductors in vacuum. Also shown are the gravitational pressure on 2-μm-thick (dashed line A) and 10-μm-thick (dashed line B) silicon membranes.

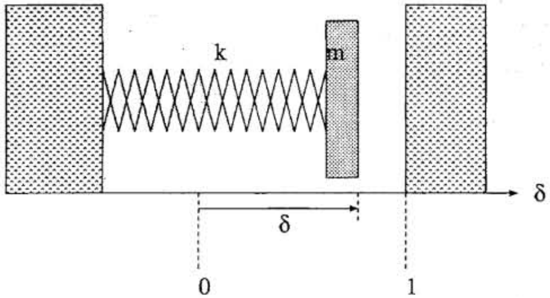

Fig. 3. The Anharmonic Casimir oscillator. Due to the Casimir effect, the moveable flat plate on the left, at $\delta < 1$, is attracted to the stationary flat surface parallel to it on the right. The wall on the left is far from the movable plate and the linear restoring force due to the spring is zero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

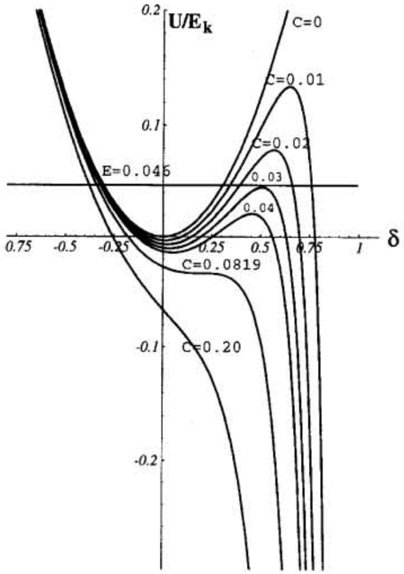

Fig. 4. The normalized potential energy per unit area of the parallel plates. $C = 0$ corresponds to the absence of the Casimir effect; this reduces the system to a simple harmonic oscillator. For $C < C_{\rm cr}(= 0.0819)$, the potential energy curve displays a pair of local extrema, corresponding to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

$$P(\delta) = P_k(\delta) + P_C(\delta) = -kw_0\delta + \frac{\Re}{w_0^4(1-\delta)^4}.$$

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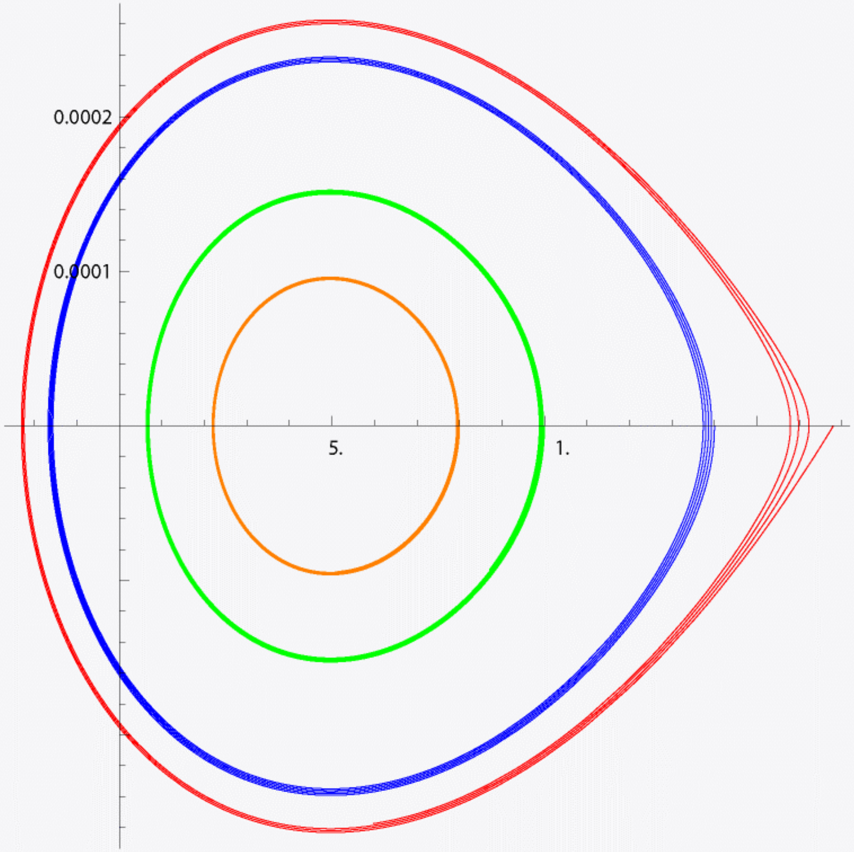

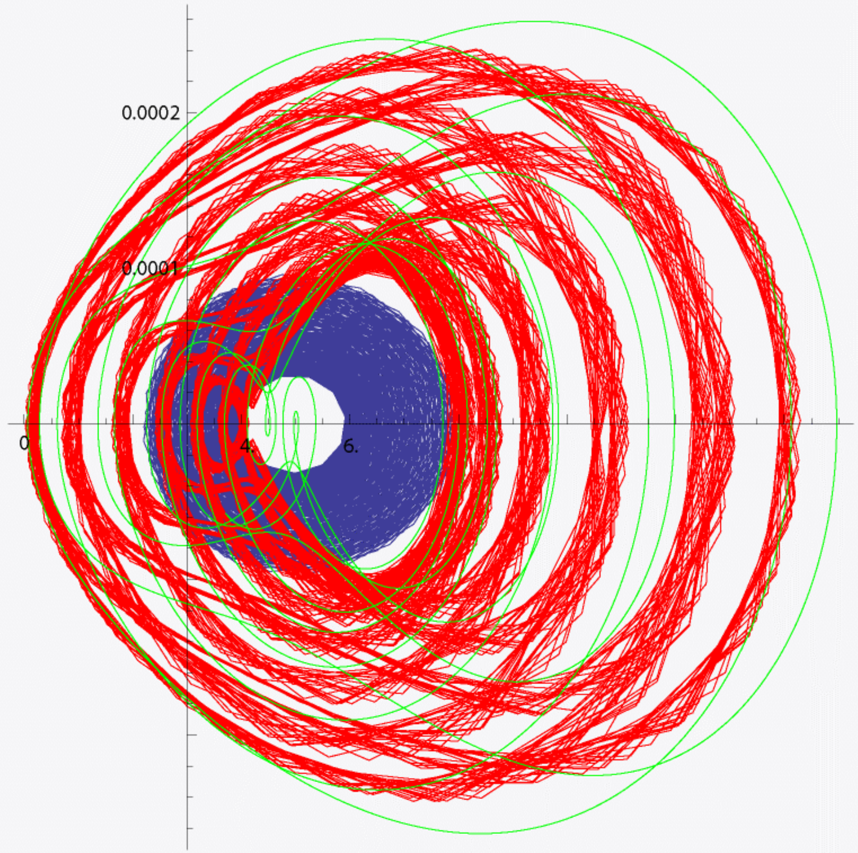

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THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 43, NUMBER 4 APRIL 1972

A Dynamic Method for Measuring the van der Waals Forces between Macroscopic Bodies

S. Hunklinger, H. Geisselmann,* and W. Arnold
Physik-Department E 10 der Technischen Universität München, 8046 Garching, Germany

(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.

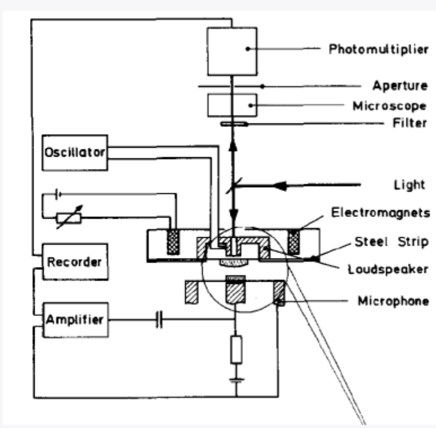
PHYSICAL REVIEW B VOLUME 19, NUMBER 12 15 JUNE 1979

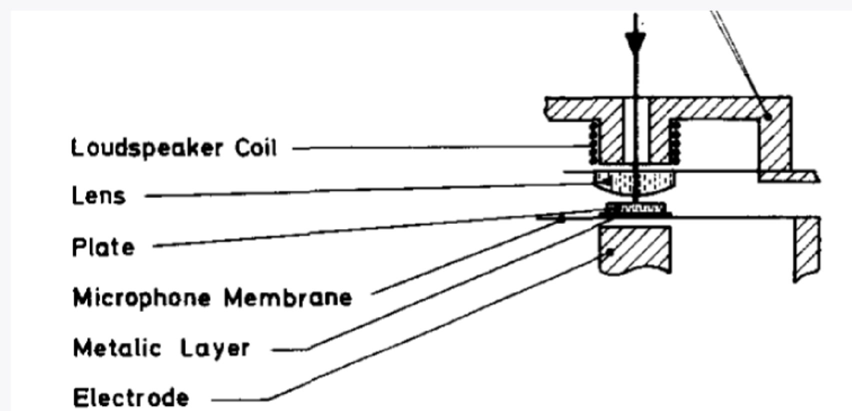
Influence of optical absorption on the Van der Waals interaction between solids

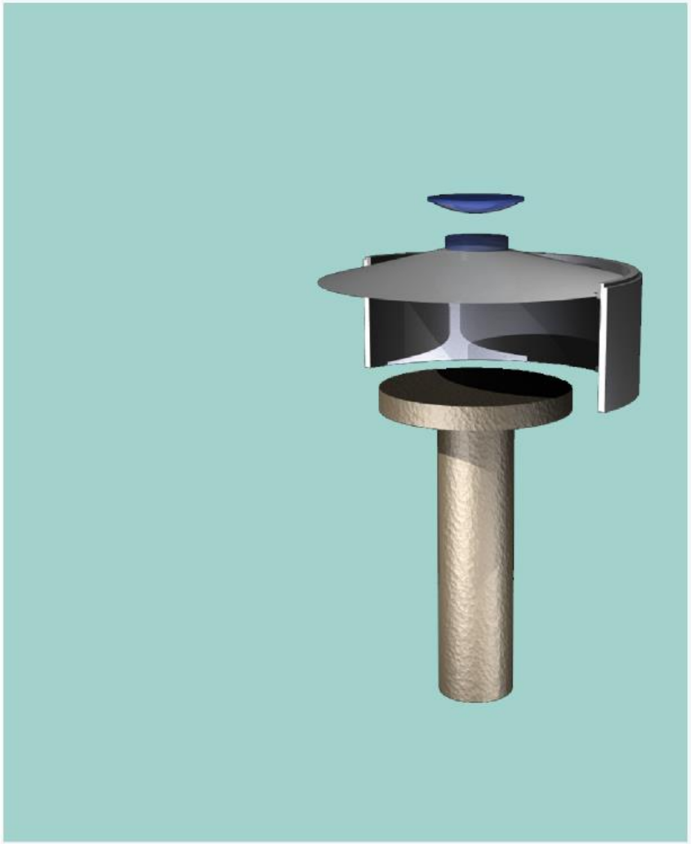
W. Arnold, S. Hunklinger, and K. Dransfeld
Max-Planck-Institut für Festkörperforschung, 7 Stuttgart 80, Heisenbergstrasse 1, Federal Republic of Germany

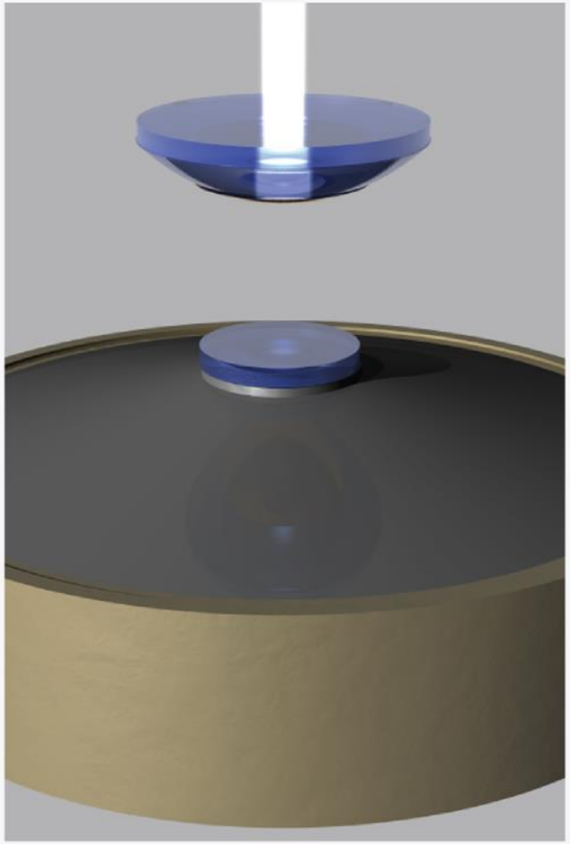
(Received 22 January 1979)

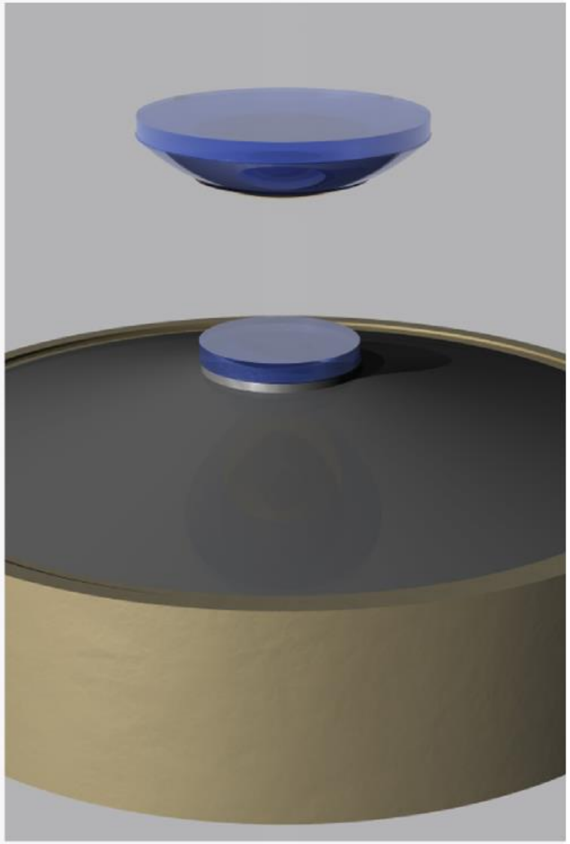
The Van der Waals forces between a variety of macroscopic bodies have been measured with high accuracy by using a new dynamic method. Between samples of crystalline quartz and borosilicate glass separated by a distance d, the most important contribution to the Van der Waals forces was found to vary as 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.





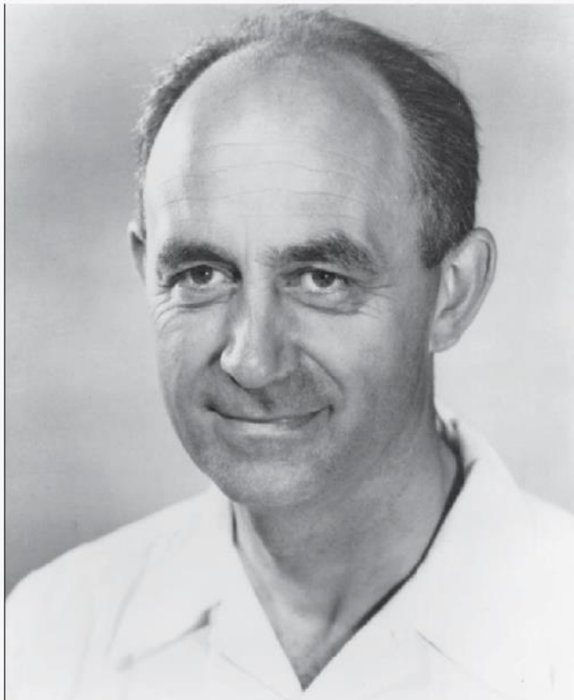






Fabrizio Pinto, *Engines Powered by the Forces between Atoms*, American Scientist, **102**, 280 (2014).

Enrico Fermi: “The Ultimate Accelerator” (1954)



Enrico Fermi: The Master Scientist — **Chapter 9** | *Fermi Humor*

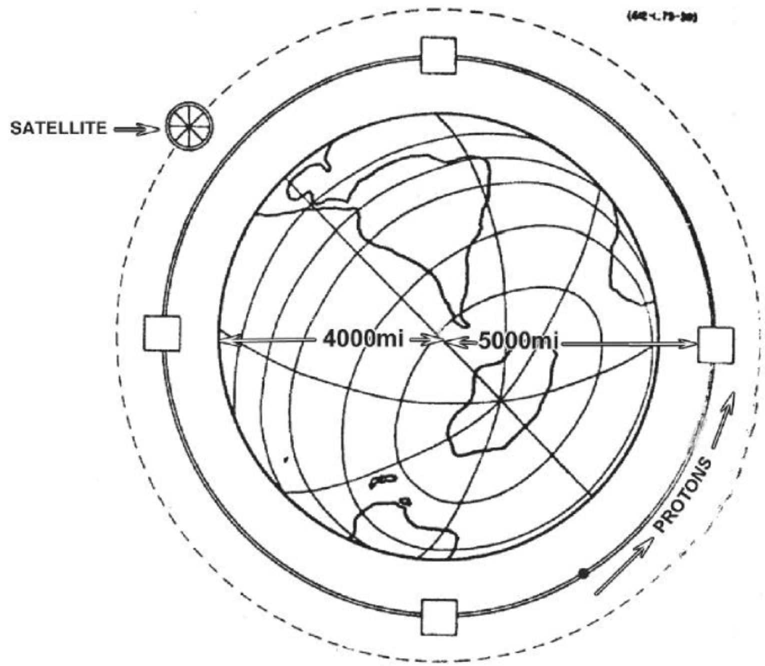


Figure 15.
Slide 3 of Fermi's talk on the ultimate accelerator. Strong focusing magnets are in earth orbit to confine a proton beam to a circle 1,000 miles above the surface of the earth.

THE ATOMIC ACCELERATOR

by

Robert Hofstadter

Department of Physics

and

High Energy Physics Laboratory

Stanford University
Stanford, California

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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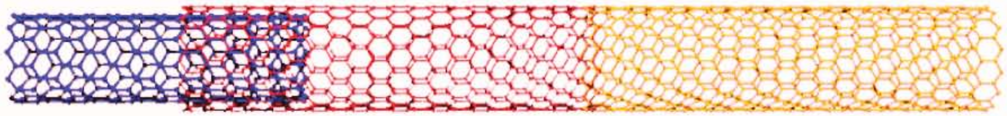

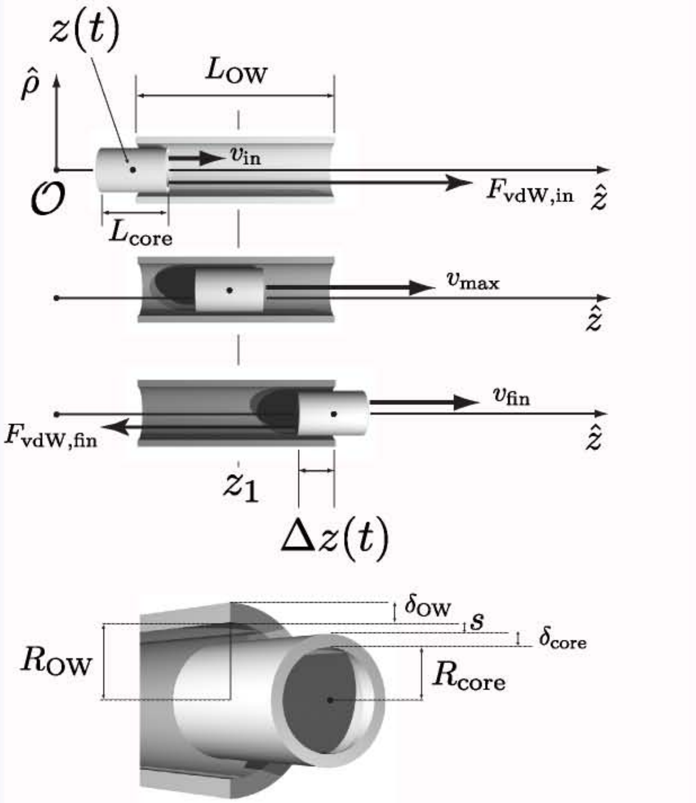

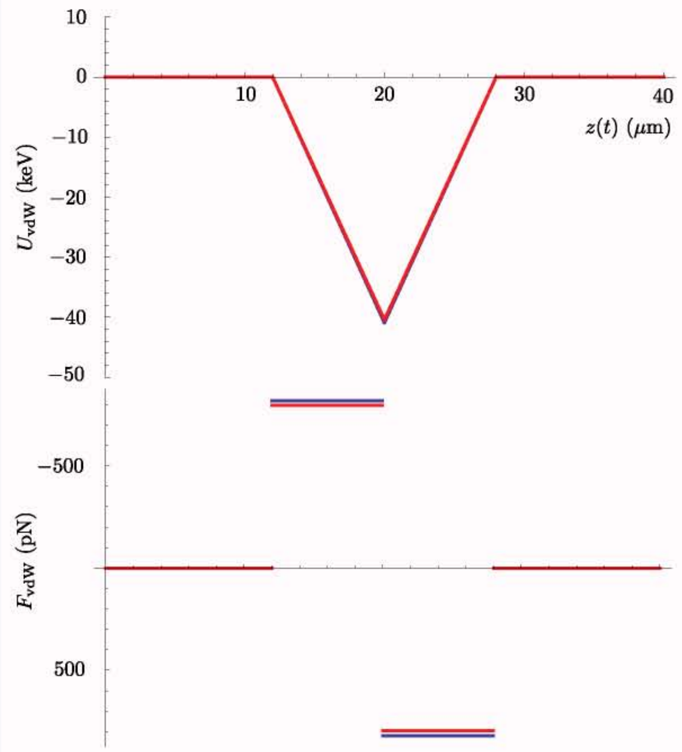

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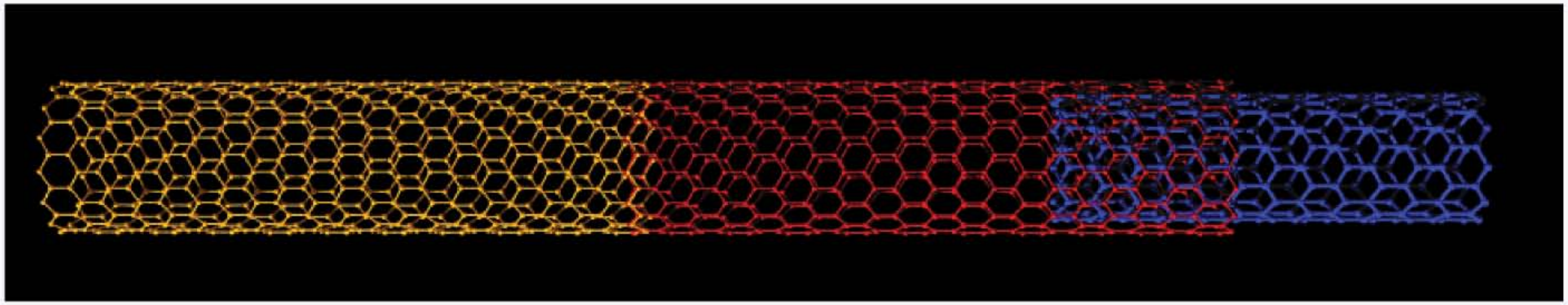

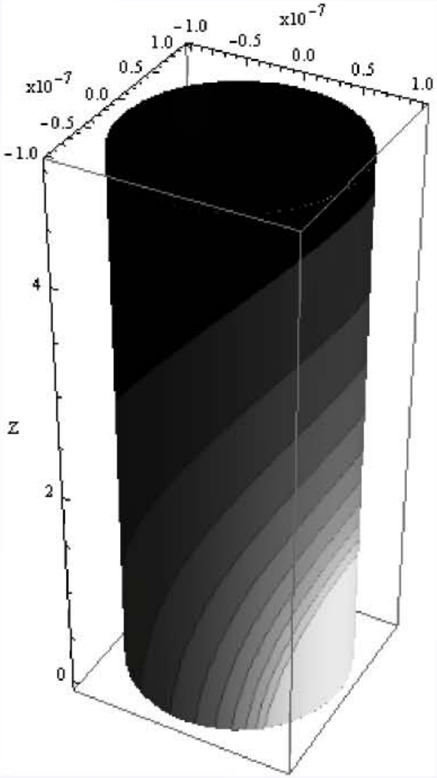

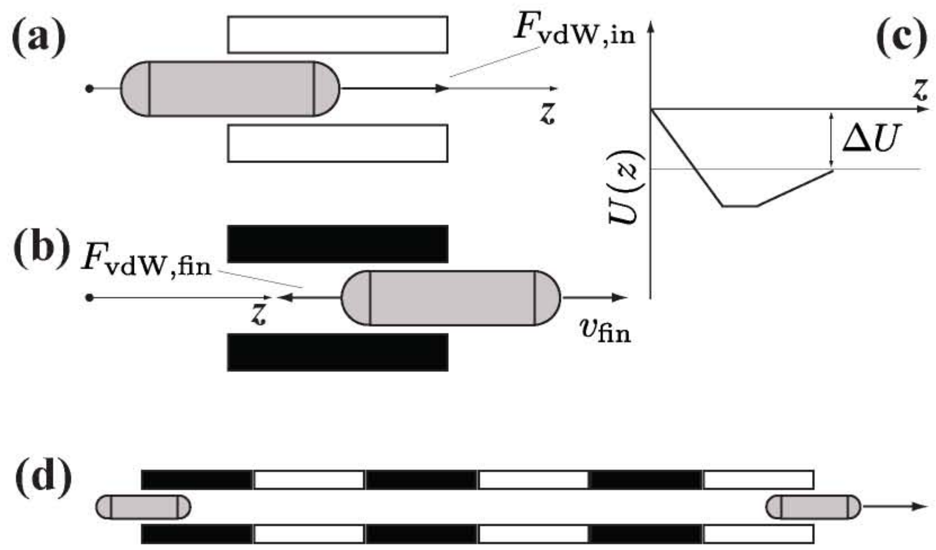

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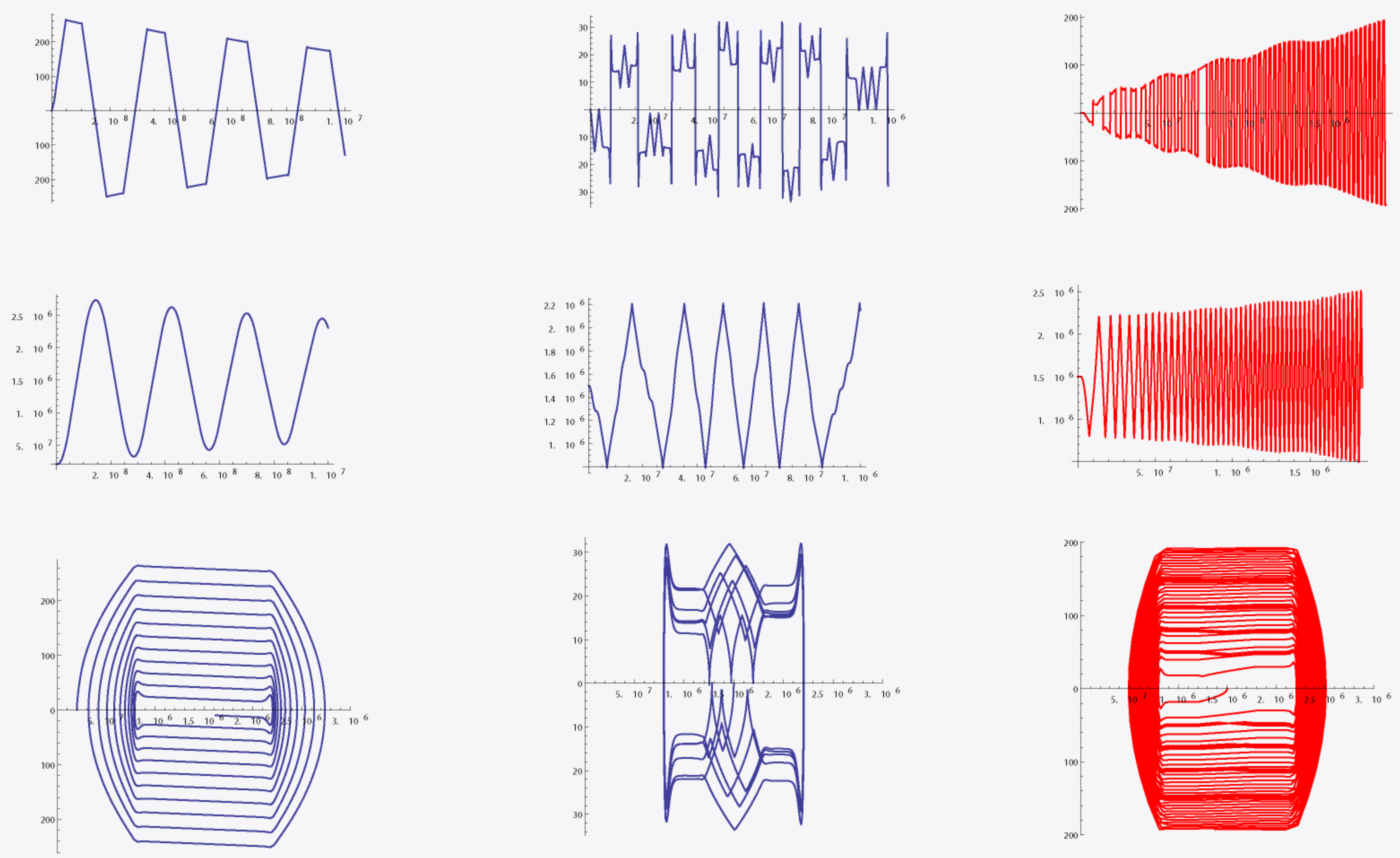

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$$U_{\mathrm{vdW,Lif}} = -\frac{\hbar S}{16\pi^2 s^2}\int_0^{+\infty} \frac{\tilde{\epsilon}_{\mathrm{c}}(i\omega_I)-1}{\tilde{\epsilon}_{\mathrm{c}}(i\omega_I)+1}\frac{\tilde{\epsilon}_{\mathrm{OW}}(i\omega_I)-1}{\tilde{\epsilon}_{\mathrm{OW}}(i\omega_I)+1}\,d\omega_I$$

$$F_{\mathrm{vdW,Lif}} = -\frac{S}{8\pi^2 s^3}\,\hbar\, I_{\mathrm{Lif}}$$

$$\epsilon_{I,\mathrm{G}}(i\omega_I) = \bar{\epsilon}_{I,\mathrm{G}}\delta(\omega_I - \omega_0) \qquad \bar{\epsilon}_{I,\mathrm{G}} = \int_0^{\infty} \epsilon_{I,\mathrm{G}}(i\omega_I)\,\delta\omega_I$$

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

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

$$v_{\mathrm{eject}} = \sqrt{\frac{2}{m_{\mathrm{core}}}\left[\Delta F_{\mathrm{vdW,z}}(n-1) - F^{\mathrm{OFF}}_{\mathrm{vdW,z}}\right]L_{\mathrm{core}}}\,.$$

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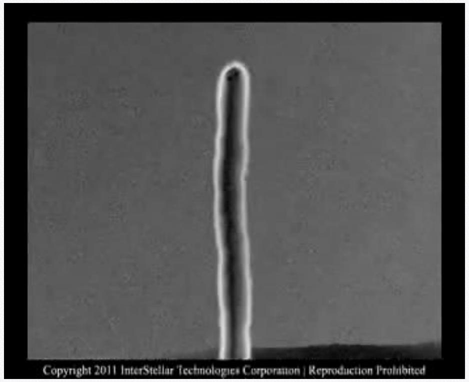
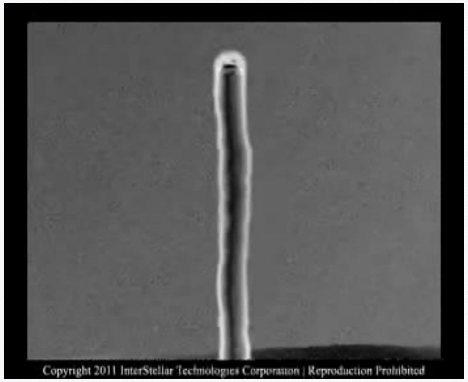
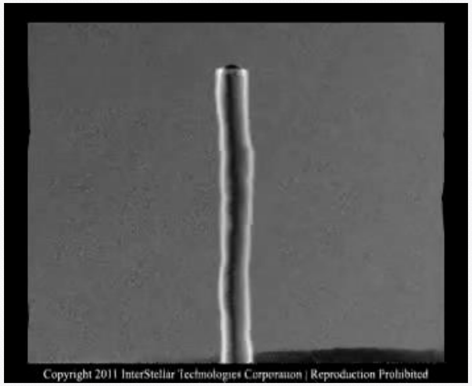
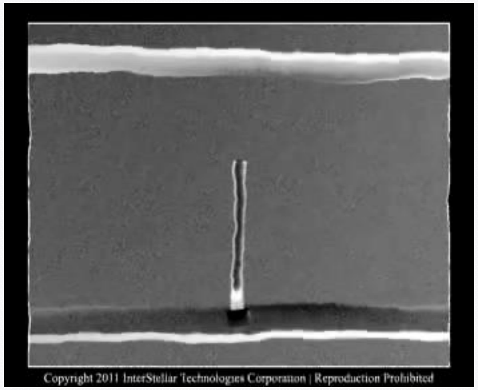
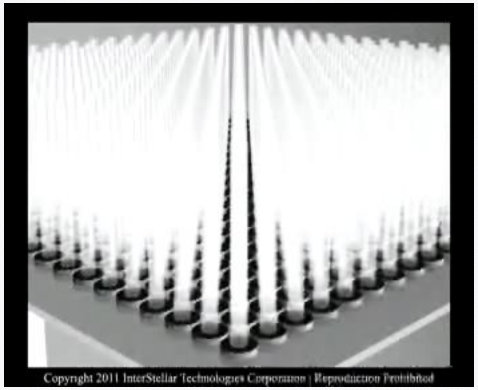
Gravitational-wave detection by dispersion force modulation in nanoscale parametric amplifers











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N° 2.

For the introduction to this paper see N° 1.

2.

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

« Nuovo Cimento », *22*, 176–188 (1921).

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.

PHYSICAL REVIEW D **73**, 104020 (2006)

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_{es}/c^2, where U_{es} 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 equivalency 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_{es}/c^2, unless the acceleration is transversal 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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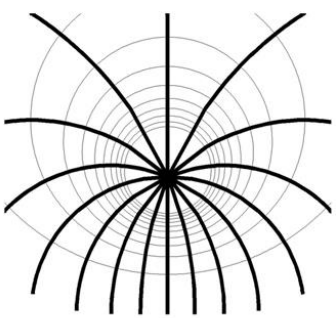

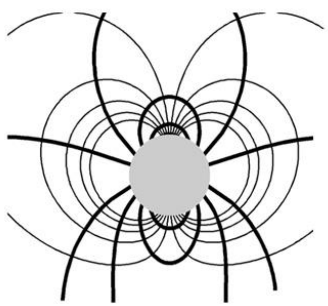

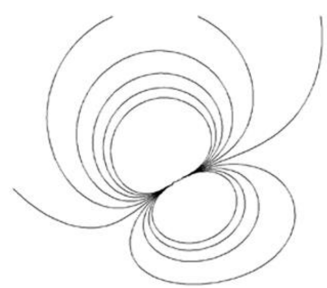

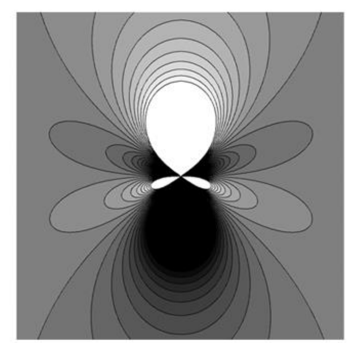

Engines Powered by the Forces Between Atoms

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 I am induced by many reasons to suspect that they may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards each other and cohere in regular figures, or are repelled and recede from one another; which forces being unknown, philosophers have hitherto attempted the search of Nature in vain.

It was not until the late 1800s that Dutch physicist Johannes Diderik van der Waals came up with a convincing explanation, based on assuming weak, short range forces between atoms. The search for Newton's "certain forces" continued until 1927, when Shou Chin Wang, a Chinese doctoral student at Columbia University, calculated the force between two hydrogen atoms using the then-novel quantum wave mechanics, 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 field*—at any point in time, the negative electrons are not evenly distributed around an atom, leading to a temporary positive charge on one side of the atom and a corresponding negative charge on the other, making the atom polarized. A nearby atom interacts with these charges, thereby producing a field that propagates back to the original atom. Finally in the 1930s this approach was fully analyzed by German-American physicist Fritz London. Because of the connections between this research and optical theory, London introduced the term "dispersion effect," and these forces collectively are called *dispersion forces*. (See also "Little Interactions Mean a Lot," March–April 2014.)

This attraction between atoms and molecules, whether known as the van der Waals force or the dispersion force, gives major clues about the cohesion of materials, and has become a standard part of even the high school-level curriculum in chemistry and physics. However, much about these forces remains a source of mystery and discovery, and they hold great potential for understanding and manipulating the world, particularly on the nanometer scale. Dispersion forces may seem to be stuck in the realm of static solids—after all, they are part of what compels fleeting gaseous particles to stick together into more substantive forms—but new methods for controlling and tailoring them could allow their use in devices that move, to transform energy and yield propulsion. By combining several new cutting-edge technologies, including carbon nanotubes, it may be possible to create entirely new mechanisms that can act as batteries or motors, storing or releasing energy as required, without the need for onboard chemical fuel.

Scaling Up

Although van der Waals forces operate at the tiny distances between atoms and molecules, their behavior also manifests on a bulk scale. The quantity that London derived, now known as the van der Waals–London potential, decays with distance between atoms, but is also proportional to how much the electrons in the atoms are free to move around, which affects their polarizability—if the electrons are so stuck in place that they cannot alter their position in relation to another atom's dipole field, they will not be able to respond to those induced charges. Additionally, London proposed that dispersion forces are additive, so that the total force between two objects should be the sum of all forces exerted by atoms in one body on all atoms in the other. Logically, the van der Waals potential should therefore be approximately proportional to the number of atoms in each slab squared. These results imply that the van der Waals forces between two plates can be computed by observing the optical properties of the bulk material, rather than starting from the individual atoms.

But it was also apparent from experiments, which used systems of macroscopic interacting particles dispersed in a medium (referred to as *colloids*), that the van der Waals potential between any two such particles separated by

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