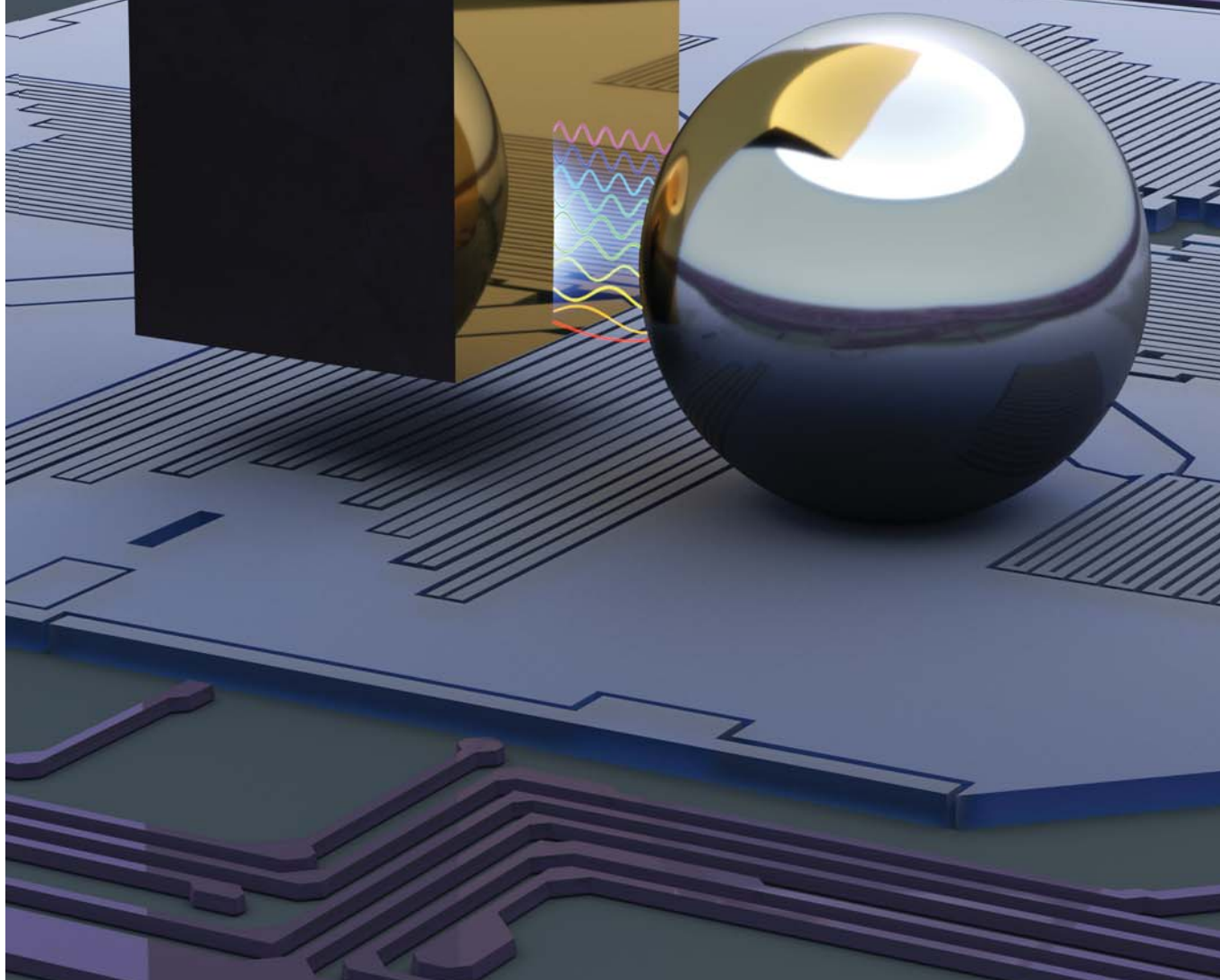


Science and technology of the **CASIMIR EFFECT**



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Alexander Stange, David K. Campbell, and David J. Bishop

Caused by simple fluctuations in space, the Casimir effect may validate theories of the cosmological constant and allow for measurements of ultrasmall magnetic fields.

In its simplest form, the Casimir effect is an attractive interaction between two uncharged and perfectly conducting plates held a short distance apart—usually less than a micron. Classically, the only attractive force acting between such plates should be gravity. But that’s vanishingly small for microscale objects. In 1948 theorist Hendrik Casimir predicted the existence of the now eponymous force on the scale of a few hundred piconewtons when the plates are held 100 nm apart.¹ Seen experimentally many times,^{2–7} the force is a nanoscale phenomenon that arises from quantum fluctuations of the electromagnetic vacuum. For a short survey of the first 60 years of research on the Casimir effect, see the article by Steve Lamoreaux, *PHYSICS TODAY*, February 2007, page 40.

Since the late 20th century, the miniaturization of sensors, actuators, and other electronic components has become routine. Integrated electronics on a chip are now pervasive—in our computers, cell phones, and all kinds of common devices. That ongoing miniaturization inevitably brings quantum mechanical effects to the fore. Fortunately, those effects can also be exploited. The development of microelectromechanical systems (MEMS) devices allows for precision measurements to be conducted in the deep submicron regime. In the past 20 years, the field of Casimir science has exploded. This article surveys current progress and the outlook for nanotechnical applications, including metrology in physical and biomedical contexts.

First, let’s step back and review the foundations of the field. To conceptually appreciate the origins of the Casimir effect, see figure 1. In a quantum vacuum, electromagnetic fluctuations appear and disappear as intermittent electromagnetic modes that span an infinite range of wavelengths in free space. But

when two perfectly conducting plates are brought close together, the long-wavelength modes get “frozen out.” That is, the optical cavity formed by the proximity of the two plates restricts the number of modes that can exist inside the cavity to those with wavelengths that are half-integral divisors of the separation. The number of modes that resides in free space has no such constraint. And that higher density of modes outside the plates produces an effective net force that pushes them inward.

More formally, the force can be determined by summing over all cavity modes. Although that quantity di-

verges, one can obtain a finite result by taking differences in the energy between plates at different separations. Using that method, in 1949 Casimir predicted¹ an attractive force per unit area at a separation a given by $-\hbar\pi^2c/240a^4$. In the classical limit, $\hbar$ goes to zero and the Casimir force vanishes. The inverse quartic dependence with distance is most unusual in physics and sharply different from the familiar inverse quadratic dependence of gravitational and electrostatic forces.

Experimentally, it’s difficult to place two large plates less than a micron apart. Doing so requires that they be strictly parallel. A now common geometry whose separation is easier to tune is that of a plate and a sphere whose radius R is much greater than a . For that configuration, the force is $-\hbar Rc\pi^3/360a^3$.

The force originally calculated by Casimir applies to perfectly conducting metal plates with electrostatically hard boundaries. A little more than a decade later, Evgeny Lifshitz extended the calculation to nonideal metals and dielectrics,

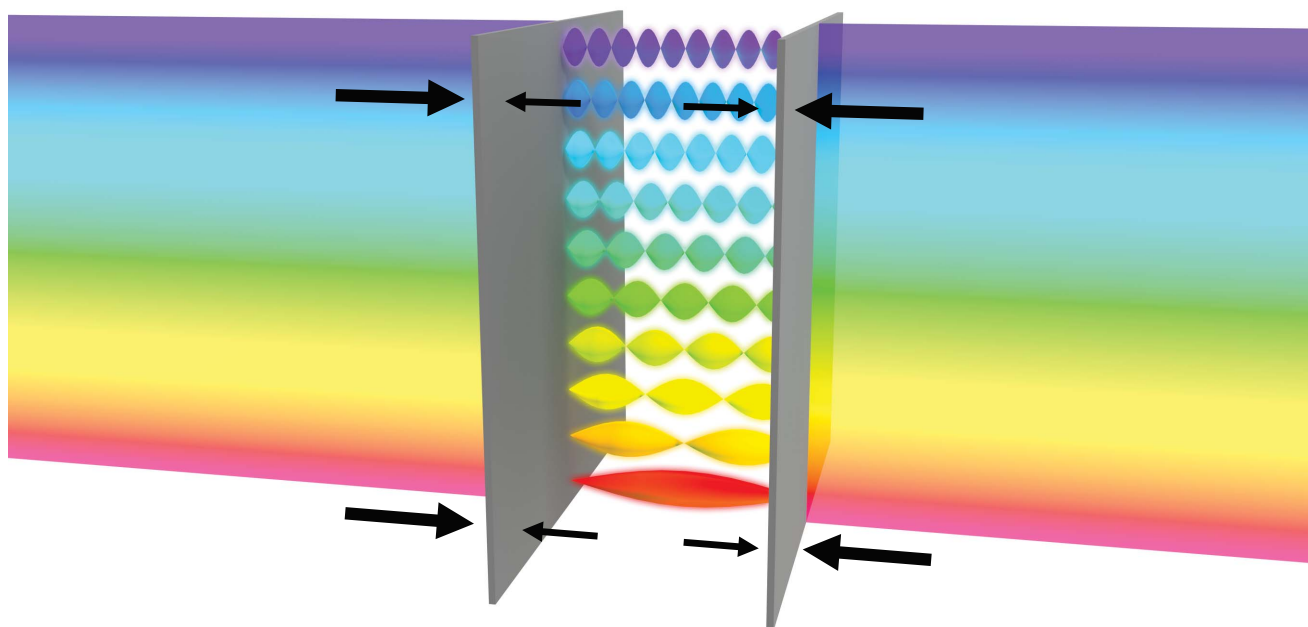


FIGURE 1. IN A QUANTUM VACUUM, free space is filled with electromagnetic fluctuations at all wavelengths. But in a Casimir cavity, typically composed of two perfectly conducting plates, boundary conditions allow for the existence of fluctuations only at half-integer wavelengths. That constraint lowers the energy density in the cavity relative to the energy density outside it and produces a net attractive interaction between the plates—provided the plates are made from the same material. For a special combination of materials, the Casimir force can be repulsive. (Figure created by Alex Stange, David Campbell, and Dave Bishop.)

including those that have rough surfaces and allow some penetration by electric fields.⁸ Dutch physicist Marcus Sparnaay provided qualitative evidence as early as 1958 that the Casimir effect is real.² But the first unambiguous quantitative observations³ came from experiments that Lamoreaux conducted using a torsional pendulum almost 40 years later, in 1997.

To appreciate the high precision and sensitivity of the Casimir force, see figure 2, which shows an early measurement using the same kind of torsional pendulum, but mounted on a far smaller MEMS device.⁵ Taking into account correction factors for real metallic surfaces,⁶ those data agree quantitatively with theoretical predictions to within a few percent.

Today, measurements of the attractive Casimir force between

metals, especially spheres and plates, are routinely seen in a wide range of geometries and experiments. Research concerns itself with details such as the finite conductivities of the metals, surface roughness, subtly varying “patch” potentials, and detailed calculations of plate–sphere geometries that are not amenable to simple, closed-form solution.

Repulsion, torque, and dynamical effects

The simple mode-variation model shown schematically in figure 1 yields an attractive force when gold films are deposited on plates that have air or a vacuum between them. But as Lifshitz and his collaborators predicted early on,⁸ a repulsive force should also be achievable. One needs to separate the plates

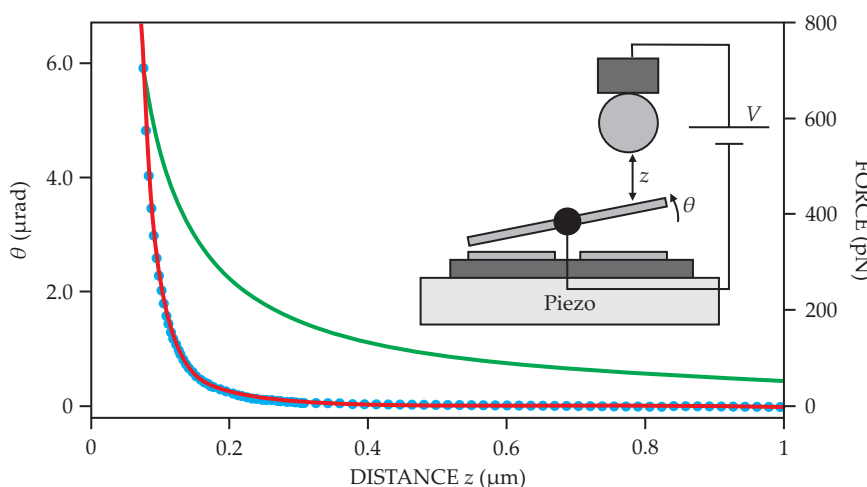


FIGURE 2. A MICROELECTROMECHANICAL TORSIONAL OSCILLATOR, sitting atop a piezoelectric stage, is positioned near a 100- μm -radius gold-coated sphere. An attractive Casimir force (the blue data points, fit to the red curve) causes the oscillator plate to rotate by an amount θ that scales with $1/z^3$, where z is the distance between the oscillator and the sphere. At separations greater than 300 nm, no tilt was detectable; below that, the attractive force increased rapidly. The voltage V on the sphere was set to a value that eliminated electrostatic contributions to the attractive force. The green curve plots the electrostatic force, whose range is much longer. (Adapted from ref. 5, H. B. Chan et al., *Science* **291**, 1941, 2001.)

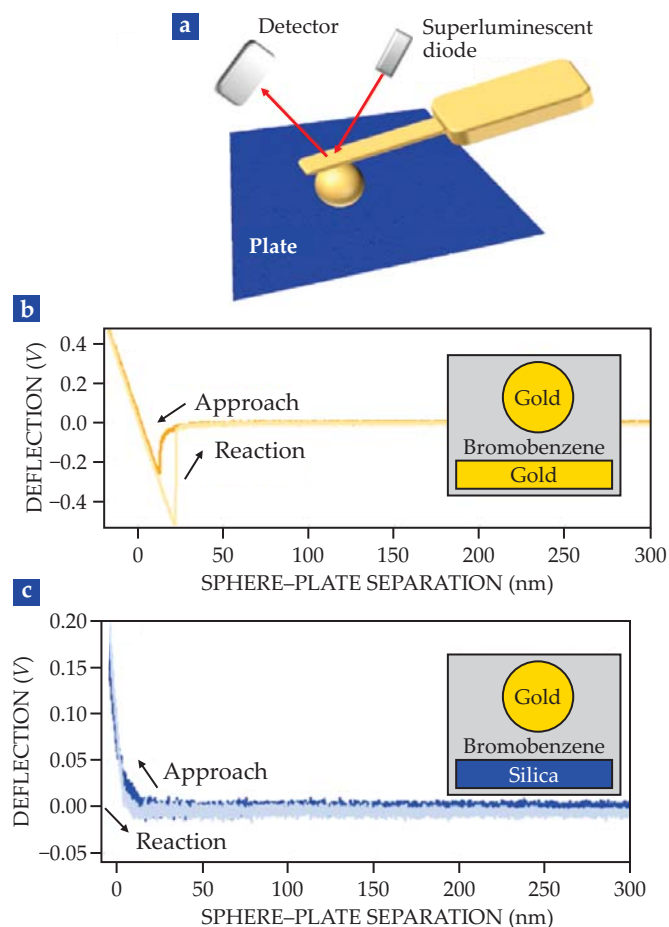


FIGURE 3. WHETHER A CASIMIR FORCE IS ATTRACTIVE OR REPULSIVE depends on the dielectric properties of the two interacting objects. **(a)** An atomic force microscope (AFM) can discern which sign is at work. In two cases, a 40 μm gold sphere attached to the end of an AFM cantilever is lowered onto a plate—either gold or silica. Sphere and plate are both inside a fluid cell containing bromobenzene. The sign of the force on the sphere is determined by the position of a light signal reflected from the cantilever into a photodetector as the cantilever is moved toward or away from the plate. **(b)** In the case where gold interacts with gold, the region of negative deflection implies that the approaching sphere is attracted to the surface and “jumps” to make contact; the attraction arises from the equal permittivities ϵ_1 of the sphere and plate. **(c)** In the case where gold interacts with silica (permittivity ϵ_2) in liquid bromobenzene (permittivity ϵ_3), the deflection is positive, signifying a repulsive force, because the three permittivities satisfy $\epsilon_1 > \epsilon_3 > \epsilon_2$. (Adapted from ref. 9.)

with a fluid, not a vacuum or air, and use a nonperfect conductor or dielectric as one of the plates. The trick is to choose materials for the plates and surrounding fluid such that the product of their permittivity differences, $-(\epsilon_1 - \epsilon_3)(\epsilon_2 - \epsilon_3)$, is positive over a wide range of frequencies.

If $\epsilon_1 = \epsilon_2$ the product is always negative, regardless of the value of ϵ_3 , producing an attractive force. If, however, one chooses materials such that $\epsilon_1 > \epsilon_3 > \epsilon_2$, then the product is positive and thus produces a repulsive force. An experiment performed by Jeremy Munday, Adrian Parsegian, and Federico Capasso demonstrated the different signs of the forces⁹ using an atomic force microscope (AFM) 12 years ago (see *PHYSICS TODAY*, February 2009, page 19). Figure 3 outlines their experiment. When a gold sphere glued to the tip of the AFM approaches the gold plate inside a fluid cell of bromobenzene, the Casimir effect pulls the objects together and the cantilever is deflected downward, a measure of an attractive force. But when the gold plate is swapped out for silica in the bromobenzene bath—a case in which the permittivities of all three materials differ and satisfy the above inequality—the cantilever deflects upward as it approaches the surface, which signifies a repulsive force.

Attractive and repulsive are not the only two kinds of forces produced by the Casimir effect. In the 1970s researchers realized that when the materials that make up the plates were optically anisotropic, they would generate a torque with respect to each other. That’s because the total free energy, which nor-

mally depends just on the separation between two parallel plates, also depends on the angle that defines their relative orientation. The conceptually obvious way to demonstrate the effect would be to rotate two birefringent crystals relative to each other and measure the torque as a function of distance between the crystals. But the difficulty of keeping two large plates parallel complicates the measurement, as does the presence of dust and surface roughness.

Munday’s group attacked the problem more cleverly, by replacing one of the birefringent plates with a liquid crystal.¹⁰ Munday and his students took a solid birefringent crystal, capped it with a layer of aluminum oxide a few tens of nanometers thick, and then placed a liquid crystal atop that. The liquid crystal wets the stack, forming a trilayer structure, and the aluminum oxide film behaves much like the vacuum gap in conventional Casimir-force experiments. The Casimir torque caused the orientation of the liquid-crystal birefringence to rotate until its optical axis aligned with the underlying solid crystal to minimize the free energy.

The coupling between the two different birefringent materials was varied by making multiple samples with differing thicknesses of aluminum oxide. The researchers then measured the extent of the rotation by shining polarized light through the stack and found that the magnitude of the torque decayed with a power-law dependence and had a $\sin 2\theta$ dependence on the angle. (See the Quick Study by Munday, *PHYSICS TODAY*, October 2019, page 74.)

Those experimental and theoretical results are more than just demonstrations. They point to future work in which the Casimir force can be used to manipulate nanoscale objects. In MEMS devices, high surface-to-volume ratios often result in unwanted stiction that could be mitigated with a repulsive Casimir interaction. What’s more, by producing attractive and repulsive forces and torque at the nanoscale, one can create, at least conceptually, a micro-tractor beam for moving quantum dots, nanowires, bacteria, viruses, and other minuscule objects.

In the dynamic Casimir effect (DCE), photons are created by a rapid change in a system parameter, such as an electromagnetic boundary condition. For example, a mirror in an optical cavity moving rapidly at a frequency f generates pairs of photons with frequency $f/2$ from the vacuum. Moving a mirror at relativistic speeds is no mean feat, and researchers have relied

on changing another system parameter such as the index of refraction instead. The effect has been seen in superconducting circuits, a Josephson metamaterial, a Bose–Einstein condensate, and photonic crystal fibers.¹¹

How is this related to the static Casimir effect? Imagine a mirror moving slowly. The quantum fluctuations can easily keep up with the mirror, and their energy, stored in the modes of a cavity, can give rise to attractive or repulsive forces. If the mirror is accelerated to relativistic speed, the virtual particles that pop into existence get separated from their partners and produce real photon pairs. The dynamic analogue is a way to essentially mine the fluctuations by stripping photons from the pairs. In the static Casimir effect, the fluctuations produce a force; in the DCE, they produce photons.

Searching for the Casimir energy

The Casimir effect emerges from fluctuations of the quantum vacuum, but its details depend directly on the nature of the materials that make up the Casimir cavity. Those details thus involve the coupling between the electromagnetic field and the walls. In the conventional Casimir effect between two perfect conductors separated by a vacuum, the positive energy density of the modes inside the cavity is less than that outside the cavity. An important question is, Can that difference in energy—the Casimir energy—be directly detected, and if so can it be exploited to reveal any novel physical phenomena?

In 1988 Michael Morris, Kip Thorne, and Ulvi Yurtsever speculated that this Casimir energy vacuum could be used to stabilize the existence of a wormhole and thus lead to the possibility of superluminal travel.¹² The Casimir force also has been invoked in connection with the cosmological-constant problem—the so-called vacuum catastrophe—and dark energy in the universe. But the wide discrepancy between the estimates of the background energy density of the universe and the energy density that would result from naïve calculations of the quantum vacuum energy fluctuations remains unresolved.

Furthermore, the Casimir effect can be formulated and Casimir forces computed without reference to zero-point fluctuations.¹³ Hence, experimentalists hope to be able to measure a physical effect that can be attributed unambiguously to the existence of the Casimir energy in order to confirm the existence of what has to date simply been used as a theorist’s tool.

One possibility recently investigated is a test of whether a Casimir cavity can shift the zero energy and alter the features of well-known phase transitions such as superconducting, melting, freezing, or magnetic transitions. Theorist Giuseppe Bimonte and others have argued along those lines to suggest that one can use a Casimir cavity to shift the critical field of a superconductor.¹⁴ The sharp change in resistance that accompanies the superconducting transition could, at least in principle, detect the small changes caused by Casimir-induced variations in energy. Bimonte argues that a Casimir cavity introduces an extra free-energy term, E , such that the new critical

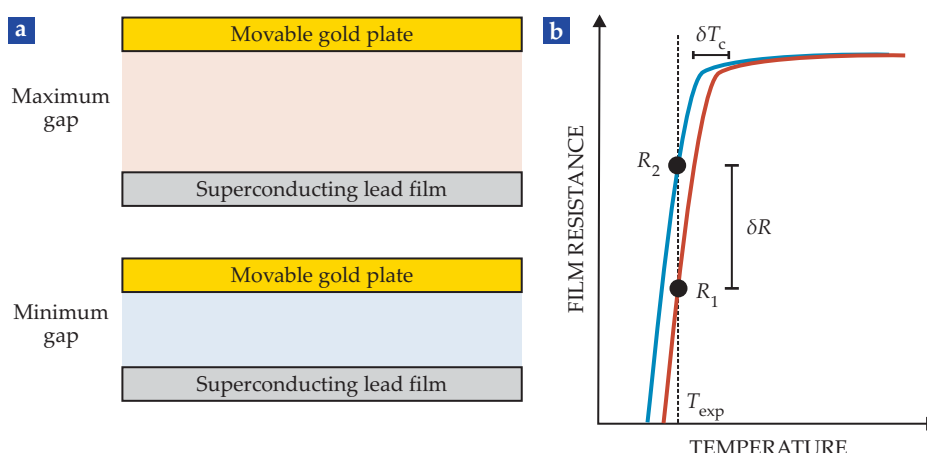


FIGURE 4. CAN A CASIMIR CAVITY CHANGE the critical temperature of a superconductor? We set out to answer that question experimentally this year. **(a)** A microelectromechanical system with a thin superconducting lead film deposited near a movable gold plate forms a tunable Casimir cavity. Theory predicts that a change in the Casimir free energy—via a change in size of the cavity—will produce a change in the condensation energy of the Pb superconductor and therefore in the critical temperature T_c of its superconducting transition. **(b)** With the temperature T_{exp} of the system set in the middle of that transition, we modulate the cavity size and search for small shifts in δT_c by monitoring any changes δR in the film’s resistance. (Adapted from D. Pérez-Morelo et al., *Microsyst. Nanoeng.* **6**, 2020, doi:10.1038/s41378-020-00221-2.)

magnetic field $H_c(T)$ required to destroy the superconductivity becomes

$$H_c(T)^2/8\pi = E_{cond} + E,$$

where E_{cond} is the condensation energy of the superconductor. In addition to developing the theory, Bimonte and his colleagues have conducted an extensive series of experiments looking for the effect by comparing the critical magnetic fields and temperatures of many similar superconducting aluminum thin films, either inside or outside a Casimir cavity. To date, however, they have not observed any unambiguous signs of a shift in the critical field, at least in experiments performed with sub-millikelvin temperature resolution.

Figure 4 outlines a different approach that we’ve recently taken to detect the shift. The experiment consists of a MEMS device with a lead thin film underneath a suspended gold plate. The two surfaces make a Casimir cavity, in which the bottom plate is a superconductor held fixed and the top is an oscillating gold surface. That arrangement allows one to vary the cavity size and simultaneously probe changes in the critical temperature of a single Pb film; that is, it lets us avoid having to compare several samples piecemeal.

In the experiment, we cool the system to the superconducting transition temperature T_c and then oscillate the gold plate and thus the size of the Casimir cavity. By monitoring the lead’s resistance, we’re able to search for small shifts in T_c with a resolution of a few tens of microkelvin. Like Bimonte and collaborators, we’ve also not yet detected any shifts. However, it is probably possible to extend the experiment’s resolution into the nanokelvin regime using existing technologies. What’s more, experimental null results of this kind constrain the effects we

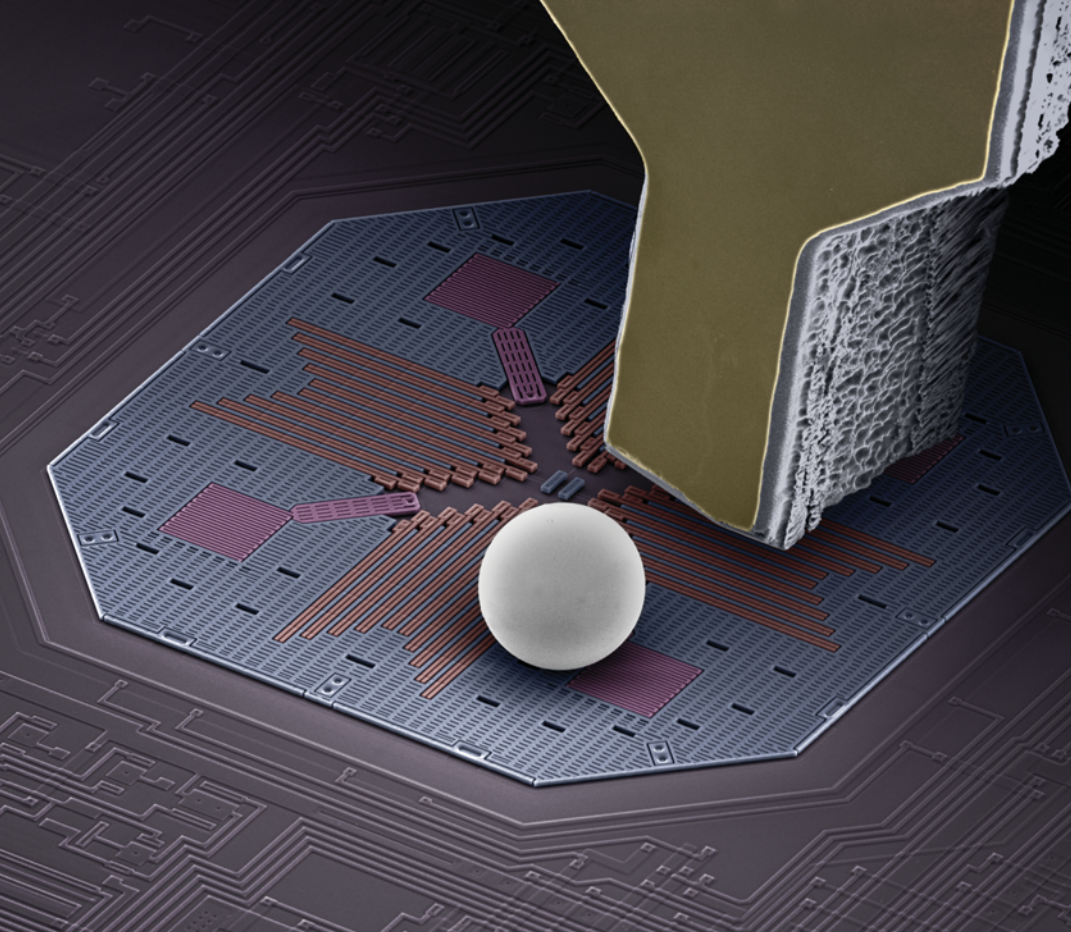


FIGURE 5. CASIMIR METROLOGY, DEMONSTRATED. A microsphere is glued to the platform of a commercial microelectromechanical-system accelerometer using a few picoliters of adhesive. It forms one half of a Casimir cavity. The other half is formed by moving the gold-coated electrode close to the sphere. The Casimir force is detected and measured using electronic sensors (orange) on the accelerometer, which pick up any motion caused by the electrode nudging the movable plate to which the sphere is attached. This device, with all the electronics integrated onto a chip, opens the door to Casimir-based metrology. (Adapted from ref. 15, A. Stange et al.)

are seeking, and refining the theories to better guide the search for the Casimir energy is an active area of research.

Although daunting, such experiments may bear on other unresolved issues of fundamental physics. Indeed, if the Casimir energy exists and can alter phenomena such as the temperature at which a phase transition occurs, then an entirely new range of devices and technologies may emerge.

Casimir metrology

Quantum metrology refers to the use of quantum mechanical phenomena for measurements well beyond what can be accomplished with classical systems. Examples abound: Superconducting quantum interference devices (SQUIDs), cold-atom interferometers, and squeezed atomic states have revolutionized high-precision measurements, but they tend to come at a substantial cost in terms of size, weight, and power requirements (SWaP). For example, SQUIDs require bulky cryogenic hardware. Cold-atom systems are similarly complex and require that a significant collection of optical components be miniaturized. Unfortunately, no current approach will allow for few-millimeter, chip-scale solutions in the foreseeable future.

Casimir-enabled quantum metrology might change that. Chip-scale devices could harness the Casimir effect and exploit it for widely applicable, room temperature, low cost, low SWaP measurements. As an example, biological systems almost never use quantum-enabled metrology given the difficulty of bringing all the measurement hardware into operation in a typical biological research or clinical setting. Yet researchers dream of having a single, millimeter-scale chip to do the job for both *in vitro* and *in vivo* applications. Breakthrough applications include magnetocardiography, measuring the magnetic fields produced by electrical currents in the heart,

and magnetoencephalography, noninvasively measuring ongoing brain activity using sensitive magnetometers. The platform one needs for such a sensor requires that the electronics of an existing technology be placed on a chip-scale Casimir system. Figure 5 shows one such system developed by two of us (Stange and Bishop) and our collaborators.¹⁵ It essentially modifies a MEMS accelerometer by incorporating a Casimir cavity. We bonded a micron-sized sphere to the accelerometer platform with picoliters of glue, so that it would be held fixed as a mobile electrode is brought close and the sphere-electrode pair behaves as a Casimir sensor. The accelerometer, which detects forces as small as piconewtons, is thus modified to a Casimir metrology device, an important first step in moving Casimir physics from the lab to the commercial world.

The Casimir effect can be used in various ways for metrology. One approach is to create a parametric amplifier that is modulated by the Casimir force. Such a device leverages the inverse quartic or cubic dependence on distance, as discussed earlier. In a sphere-plate geometry, one would oscillate the sphere at one frequency f and modulate the plate position at $2f$. The Casimir force couples the two objects and pumps energy into the primary resonance. Another set of electrodes controls the distance between the objects with an applied voltage. A few years ago two of us (Campbell and Bishop) demonstrated how the coupling can produce a system in which the resonant amplitude depends on the tenth power of the applied voltage.¹⁶ That approach is reminiscent of an earlier 2001 experiment that used Casimir coupling to an oscillating sphere to create a nonlinear response in the system.⁵

Nanopatterning

So far, this article has dealt with planar surfaces and with sphere-plane systems. In either case, surface roughness has been treated as an imperfection that needs to be measured and accounted for using Lifshitz theory.⁸ However, it can become a feature in some situations—something deliberately

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added to the surface that makes the coupled system more interesting to study.

Nanopatterning metallic surfaces can yield a rich palette of advantageous effects. Applications such as extraordinary light transmission, surface-enhanced Raman scattering, and single-molecule spectroscopy made possible by plasmonic enhancements are a few well-known examples, although they work over a narrow range of frequencies. (See the articles by Katrin Kneipp, *PHYSICS TODAY*, November 2007, page 40, and by Mark Stockman, *PHYSICS TODAY*, February 2011, page 39.)

With metamaterials, engineers can control the local electric and magnetic properties of a material and endow it with optical properties that cannot be obtained with conventional films. Nanopatterning, a common method for forming a conventional material into a metamaterial, allows the customization of surfaces in a vast variety of ways. Whether a Casimir force is attractive or repulsive, as we've seen, is determined by the dielectric response of materials that make up the Casimir cavity. Researchers are using plasmonics and metamaterials to modify the Casimir force in ways that can't be done using planar surfaces with conventional materials. Nanopatterning may become a powerful tool to explore many new phases and states of matter that emerge from interactions between the plates.¹⁷

Because the Casimir effect is a room-temperature, nanoscale phenomenon, its use for practical measurements is a real possibility in the near future. We are particularly enthusiastic about the prospects for its biological and medical applications. SWaP considerations are particularly acute in those fields, and chip-scale, room-temperature devices could, among other advances, be able to detect ultrasmall magnetic fields. We believe

that the Casimir effect may someday save lives through technologies like quantum-enabled magnetometers for ultrasensitive cancer detection.

Hendrik Casimir passed away in 2000. He lived long enough to see his prediction quantitatively verified but not to appreciate the current explosion of activity. Those of us who work in the field like to think he would be extremely proud of what he created.

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