QUICK STUDY

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A new twist on the quantum vacuum

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A subtle macroscopic effect in the space between two birefringent plates produces a measurable Casimir torque.

One usually imagines a vacuum as empty space devoid of any matter. That picture isn't quite accurate when quantum mechanics is taken into account. Emptiness turns out to be an illusion: The real vacuum is full of activity in the form of quantum fluctuations—sometimes thought of as virtual particles that appear and disappear so quickly that they don't violate Heisenberg's uncertainty principle. In this Quick Study, I discuss how electromagnetic fluctuations can give rise to forces and even torques between macroscopic objects without the need for any other interactions. Indeed, the quantum mechanics of a vacuum may prove to be an exciting tool for engineering nanoscale devices.

Forces from nothing

In the late 1940s while working at Philips Laboratory Eindhoven in the Netherlands, Dutch physicist Hendrik Casimir developed a theory to describe the interaction forces he observed in colloidal suspensions. Intrigued by the notion of quantum fluctuations of electromagnetic fields and by conversations with Niels Bohr, Casimir considered what would happen in a different scenario involving two parallel, uncharged, metallic plates.

In a classical vacuum, nothing happens. But in a quantum vacuum, he realized, the presence of the closely spaced plates—essentially an optical cavity—would influence the fluctuating fields (see, for example, the Reference Frame by Daniel Kleppner, Physics Today, October 1990, page 9, and Physics Today, November 2011, page 14). More specifically, conductive plates force the electric and magnetic fields to go to zero at the boundaries, and only a subset of the fluctuations can exist between the plates; the largest wavelengths are excluded simply because they do not fit.

The plates effectively reduce the energy density, often called the zero-point energy, associated with those quantum fluctuations. The closer the plates, the lower the zero-point energy. Because nature likes to minimize the energy of a system, the two plates should be attracted to each other—an interaction referred to as the Casimir effect.

Within 10 years of Casimir's prediction, an experiment by Dutch physicist Marcus Sparnaay confirmed the existence of the Casimir force between two parallel plates. In Sparnaay's own words, the experiments "do not contradict Casimir's theoretical prediction." That humble phrasing reflected the difficulty of measuring such small forces while keeping the plates parallel and in close proximity—typically below a micron—and removing electrostatic interactions and other artifacts.

Around the same time, 1956, Russian chemist Boris Derjaguin realized that replacing one of the plates with a sphere would simplify the measurement: Researchers would no longer need to worry about keeping the plates parallel. Although the sphere–plate geometry did improve detection, not until the 1990s did modern measurement techniques usher in a new wave of Casimir force experiments. (See the article by Steve Lamoreaux, Physics Today, February 2007, page 40, and Physics Today, February 2009, page 19.)

From forces to torques

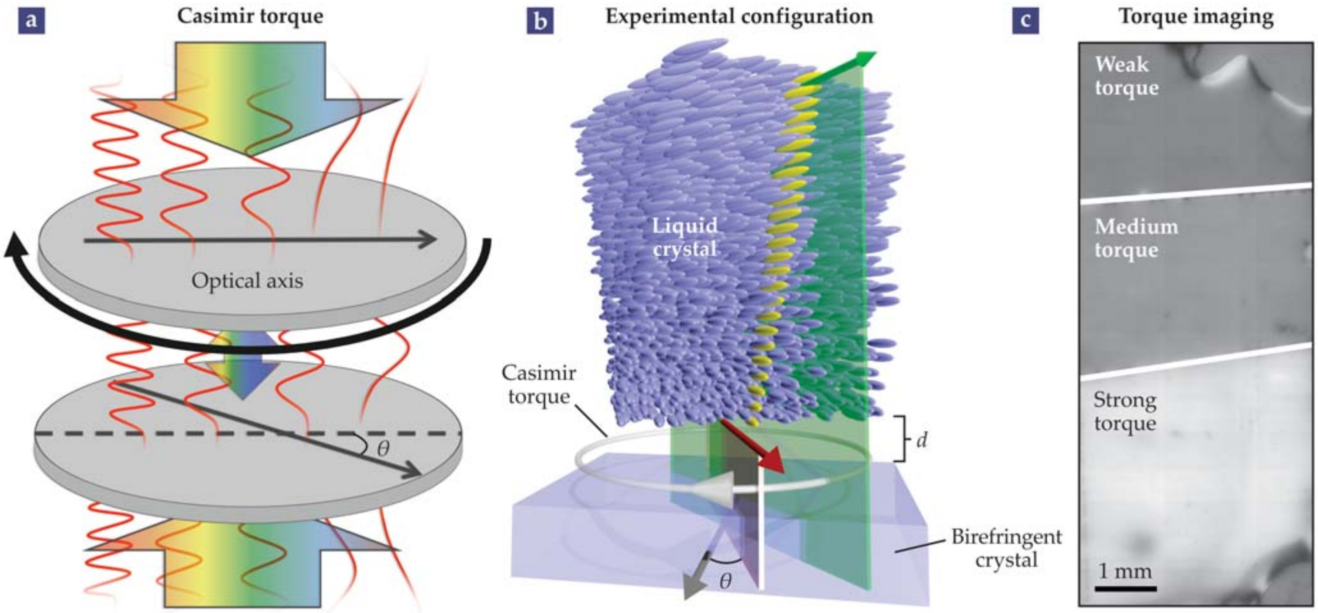
Casimir's theory describes the force between metal plates. But what happens when the plates are not perfect conductors? Theorists Igor Dzyaloshinskii, Evgeny Lifshitz, and Lev Pitaevskii answered that question in 1961 when they generalized Casimir's result to the case in which the plates are described by arbitrary, isotropic dielectric functions. Today their theory is used in comparisons to experiment; the optical properties of the actual metals used in the experiments are incorporated as variables into the theory.

In the 1970s a new configuration was considered: What if the optical properties of the plates are anisotropic—for example, when using birefringent crystals such as calcite? In that case, the total free energy of the system depends not only on the separation between the two parallel plates but also on the angle θ that defines their relative orientation. The system should exhibit a torque that causes the plates to rotate into a position of minimum energy—a Casimir torque.

Minimum energy is reached when the optical axes with the highest refractive index align. The theory for that idea was worked out by Adrian Parsegian and George Weiss and independently by Yuri Barash. For relatively small separations, generally less than a few tens of nanometers, they found that the torque has a $\sin 2\theta$ dependence and is inversely proportional to the separation squared.

As with the Casimir force, several technical issues complicate measuring the Casimir torque. Two relatively large-area plates need to be kept parallel and at submicron separations. One plate also needs to freely rotate relative to the other, and that rotation must be detectable above background noise and artifacts. A way to perform such an experiment is to suspend one birefringent plate above another using a torsion rod.

The twisting of the rod induced by the Casimir torque could be measured optically or electronically to determine the rotation angle. But parallelism, dust removal, and surface imperfections turn out to be difficult to control in that setup. Another possibility is to perform experiments in which one plate is levitated above another either using optical tweezers in vacuum



IMAGING THE TWIST FROM VACUUM. (a) When two optically anisotropic plates form a narrowly spaced optical cavity, the energy associated with quantum fluctuations between them depends on their orientation. To minimize the free energy of the system, the Casimir torque rotates one plate relative to the other until their optical axes align. **(b)** This configuration illustrates my group's recent experiment to measure the Casimir torque between a liquid crystal and a solid birefringent crystal. A thin isotropic layer of material separates the crystals by a variable distance *d*. The yellow rods illustrate the extent to which the liquid-crystal sample twists from top to bottom; the green and red arrows show the average direction of the liquid at the two endpoints. The dark gray arrow in the birefringent crystal depicts the crystal's optical axis. **(c)** Shining polarized light through the liquid and solid crystals offers a way to reveal the Casmir torque. A sample is prepared with three spacing-layer thicknesses that separate the liquid crystal from the solid birefringent crystal. Viewed between crossed polarizers, the image brightness is proportional to the strength of the torque. A thinner spacing layer *d* results in a stronger torque and hence a brighter image.

or using electrostatic or dispersion forces in a fluid. Unfortunately, those setups suffer from many of the same problems as experiments involving torsion rods.

To circumvent those problems, my group developed an alternative experiment that enabled the first quantitative measurement of the Casimir torque. The trick was to replace one of the birefringent plates with a liquid crystal, as shown in the figure. Liquid crystals contain birefringent molecules that can have local and long-range order. They behave much like solid birefringent crystals but can also wet another surface and rotate at the molecular level.

For our experiment, we used a solid birefringent crystal on which we deposited a thin—less than 30 nm—optically isotropic layer of aluminum oxide. That layer separates the solid crystal from the liquid crystal, much like the vacuum gap in Casimir-force experiments. Once the liquid crystal is placed atop the aluminum oxide, it wets the surface to form a three-layer stack: a solid birefringent crystal, aluminum oxide, and liquid crystal. The thickness of the spacer layer determines the distance between the solid and liquid crystals, and it can be varied by making multiple samples. The Casimir torque then rotates the liquid crystal so that its optical axis aligns with that of the solid crystal. We detected the rotation by measuring the polarization rotation of an incident light beam using an optical microscope.

The experiment, published in 2018, confirmed many of the predictions made by Parsegian, Weiss, and Barash. It showed that the torque decays with a power-law dependence on the separation and has a sin 2θ dependence on the angle. The optical properties of the crystal substrate and of the liquid crystal affect the magnitude of the torque and its sign (clockwise or counterclockwise rotation). My lab has measured torque densities as small as a few nanonewton meters per meter squared on surfaces separated by tens of nanometers.

Quantum effects in the real world

Beyond a confirmation of a quantum effect predicted decades ago, the measurement of the Casimir torque sets the stage for engineering vacuum fluctuations to modify how nanoscale and microscale devices work. In the world of microelectromechanical systems (MEMS), the Casimir force and the related van der Waals force are thought to have an important effect on surface-adhesion phenomena that cause devices to break. Reducing, eliminating, or even reversing the Casimir force among MEMS devices could ameliorate the problem.

Rather than being hindrances, the Casimir force and torque may perhaps give rise to more sensitive accelerometers and torsion sensors. What's more, the fact that the Casimir torque can affect liquid crystals—a staple of modern display technologies—suggests that liquid-crystal applications may also be on the horizon. Among the possibilities is ultralow-power switching that requires merely a tiny voltage to break the alignment of the liquid crystal and allow light to pass or be absorbed when the crystal is placed between crossed polarizers.

Additional resources

▶ V. A. Parsegian, *Van der Waals Forces: A Handbook for Biologists, Chemists, Engineers, and Physicists*, Cambridge U. Press (2005).

▶ D. Iannuzzi et al., "The design of long range quantum electrodynamical forces and torques between macroscopic bodies," *Solid State Commun.* **135**, 618 (2005).

▶ D. A. T. Somers et al., "Measurement of the Casimir torque," *Nature* **564**, 386 (2018).

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