Dispersion forces as probes of spacetime fluctuations: Epistemology, theory, strategies for laboratory detection, and prospects for experiments in space

Fabrizio Pinto
Aerospace Engineering Department, Faculty of Engineering, Izmir University of Economics
Teleferik Mahallesi, Sakarya Cd. No: 156, 35330 Balçova Izmir, Republic of Turkey. Email: fabrizio.pinto@ieu.edu.tr

There are fundamental reasons to expect that spacetime, including both in Minkowskian and weak field, near-Earth conditions, should fluctuate. As one approaches the Planck scale, *active*, or *intrinsic*, fluctuations are predicted to appear because of the presumed quantum nature of the gravitational field, whereas *passive*, or *induced*, fluctuations originate from the quantum matter field stress tensor [1, 2]. Similarly to the case of quantum electrodynamics (QED) [3], the successful detection and characterization of such spacetime fluctuations, both via experimental and observational strategies, represents possibly the most critical future falsification test for predictions from quantum gravity theories [4, 5].

A class of experiments of ever increasing sophistication [6, 7] to attract extreme interest in the last two decades focuses on the Casimir effect [8], which is indeed a direct manifestation of fluctuations in the presence of boundary conditions [9]. In QED, dispersion interactions between nearby boundaries have been so extensively demonstrated to be dominant on the nanoscale as to have been assigned important roles in the design of nano-electro-mechanical systems (NEMS) and nanostructures [10]. In the case of the Dirac and gluon fields in hadrons, the inertial equivalent of the Casimir energy contribution plays a very important role and has been estimated at $\approx 9\%$ of the total particle mass in the MIT bag model [11]. Importantly, both attractive and repulsive Casimir forces have also been demonstrated in *classical* stochastic acoustic fields in which the cavity noise spectrum is not determined by the zero-point-field but is operator-assigned [12].

The question as to whether *gravitational* dispersion forces exist in Minkowski space – for instance, between boundaries or between gravitationally polarizable particles – seems quite natural by analogy to the above cases but it is, apparently, a relatively recent research topic. The idea that two macroscopic parallel plane gravitational wave reflectors should experience a mutual Casimir force is reported to have been suggested by Dirk Bouwmeester in the context of the theoretical treatment of a mechanism for gravitational wave reflection in superconductors [13] and it was further explored in more detail by Quach [14]. The gravitational analog to the Casimir-Polder and London-van-der-Waals forces has been treated even more recently by Ford and collaborators [15]. The limitation of the former approach is that any mechanisms leading to near-ideal gravitational wave reflection in superconductors are, for the moment, completely unverified and only speculative; in the latter, gravitational Casimir-Polder forces are found to be negligible in realistic astrophysical systems.

However, additional connections exist between gravitation and electrodynamical dispersion forces pointing to promising novel strategies for spacetime fluctuation detection to be discussed in this presentation. In particular, the effect of spacetime curvature on the Casimir force between parallel ideal reflectors has been analyzed in the weak field limit leading to theoretical confirmation that the gravitational equivalent of the negative Casimir energy manifests itself as a cavity weight defect [16]. Quantitative estimates for realistic systems have inspired an ongoing experimental attempt to achieve a dynamic detection of such a defect in superconducting Casimir cavities [17, 18]. Importantly, these theoretical results have been more recently recovered by means of the effective refractive index interpretation of the gravitational field [19]. The same approach had been earlier validated by the present author [20] starting from the classical problem of the field of an accelerated dipole [21] and by demonstrating that the gravitational equivalent of the London-van der Waals interaction energy of two hydrogenic atoms manifests itself as a weight defect potentially detectable in cold atomic traps [22].

Since dispersion forces depend on the media within which the interacting boundaries or particles are immersed [8], such a century-old optical medium analogy provides an initial intuitive motivation to search for the effects of gravitational fluctuations on the behavior of electrodynamical dispersion forces both in space and time [23, 24, 25]. In this paper, we shall consider the Maxwell equations in slightly perturbed Minkowski spacetime and we shall present detailed calculations of intermolecular forces in time-dependent gravitational wave metrics also aided by Mathematica notebooks and visualization tools. These results will be employed to illustrate the effects of stochastic gravitational wave fields on dispersion forces and the possibility of experimental detection of such phenomena. A critical point will be the role of “foreground” astrophysical and cosmological gravitational wave fields possibly contaminating tests of the fundamental quantum nature of spacetime. Following up on arguments in favor of a “Gravity Probe C” mission [26], suggestions for highly sensitive Casimir force experiments to search for gravitational field fluctuations in space will also be presented.

Finally, we shall consider the epistemological meaning of future results from such experiments, whether positive or null, and the logical connections between the Casimir effect and the quantum nature of any given field [27, 28].

References

[1] B. Hu, A. Roura, and E. Verdaguer, "Induced quantum metric fluctuations and the validity of semiclassical gravity," *Phys. Rev. D*, **70**, 044002 (2004).

[2] L. H. Ford, "Spacetime in Semiclassical Gravity," in *One Hundred Years of Relativity*, A. Ashtekar, Ed. (World Scientific, Singapore, 2005), pp. 293–310.

[3] T. A. Welton, "Some Observable Effects of the Quantum-Mechanical Fluctuations of the Electromagnetic Field," *Phys. Rev.*, **74**, 1157–1167 (1948).

[4] G. Amelino-Camelia, "A phenomenological description of quantum-gravity-induced space-time noise," *Nature*, **410**, 1065–1067 (2001).

[5] G. Amelino-Camelia, "Quantum-Spacetime Phenomenology," *Living Rev. Relat.*, **16**, 5–137 (2013).

[6] G. L. Klimchitskaya, U. Mohideen, and V. M. Mostepanenko, "The Casimir force between real materials: Experiment and theory," *Rev. Mod. Phys.*, **81**, 1827–1885 (2009).

[7] S. K. Lamoreaux, "The Casimir Force and Related Effects: The Status of the Finite Temperature Correction and Limits on New Long-Range Forces," *Annu. Rev. Nucl. Part. Sci.*, **62**, 37–56 (2012).

[8] P. W. Milonni, *The Quantum Vacuum* (San Diego, Academic Press, 1994).

[9] V. A. Parsegian, *Van der Waals Forces* (Cambridge University Press, Cambridge, 2006).

[10] F. Pinto, "Casimir forces in relativistic metrology: Fundamental physical tests and aerospace applications," *Proc. Third IEEE International Workshop on Metrology for Aerospace, Florence, Italy* (2016), Paper ID: 4292221.

[11] V. M. Mostepanenko and N. N. Trunov, "The Casimir effect and its applications," *Sov. Phys. Usp.*, **31**, 965–987 (1988).

[12] A. Larraza *et al.*, "The force between two parallel rigid plates due to the radiation pressure of broadband noise: An acoustic Casimir effect," *J. Acoust. Soc. Am.*, **103**, 2267–2272 (1998).

[13] S. J. Minter, K. Wegter-McNelly, and R. Y. Chiao, "Do mirrors for gravitational waves exist?" *Physica E*, **42**, 234–255 (2010).

[14] J. Quach, "Gravitational Casimir Effect," *Phys. Rev. Lett.*, **114**, 081104 (2015).

[15] L. H. Ford, M. P. Hertzberg, and J. Karouby, "Quantum Gravitational Force Between Polarizable Objects," *Phys. Rev. Lett.*, **114**, 151301 (2016).

[16] E. Calloni *et al.*, "Vacuum fluctuation force on a rigid Casimir cavity in a gravitational field," *Phys. Lett. A*, **297**, 328–333 (2002).

[17] G. Bimonte *et al.*, "The Aladin2 experiment: status and perspectives," *J. Phys. A: Math. Gen.*, **39**, 6153–6159 (2006).

[18] A. Allocca *et al.*, "Results of Measuring the Influence of Casimir Energy on Superconducting Phase Transitions," *J. Supercond. Nov. Magn.*, **25**, 2557-2565 (2012).

[19] B. Nazari and M. Nouri-Zonoz, "Electromagnetic Casimir effect and the spacetime index of refraction," *Phys. Rev. D*, **85**, 044060 (2012).

[20] F. Pinto, "Resolution of a paradox in classical electrodynamics," *Phys. Rev. D*, **73**, 104020 (2006).

[21] V. Petkov, *Relativity and the Nature of Spacetime* (Springer, Berlin, 2009).

[22] F. Pinto, "A trapped dipolar BEC inteferometry test of $E = mc^2$," *Int. J. Mod. Phys. D*, **15**, 2235–2240 (2006).

[23] F. Pinto, "Nanomechanical sensing of gravitational wave-induced Casimir force perturbations," *Int. J. Mod. Phys. D*, **23**, 1442001 (2014).

[24] F. Pinto, "Gravitational-wave response of parametric amplifiers driven by radiation-induced dispersion force modulation," *Proc. of the Fourteenth Marcel Grossman Meeting on General Relativity* held in Rome, Italy (2015), to appear; `http://robot.icra.it:8080/publish?publish=on&id=543`.

[25] F. Pinto, "Gravitational-wave detection by dispersion force modulation in nanoscale parametric amplifiers," *TAUP 2015: Proc. XIV International Conference on Topics in Astroparticle and Underground Physics. J. of Phys. Conf. Ser.*, **718**, 072004 (2016).

[26] C. J. de Matos and M. Tajmar, "Testing the Influence of the Gravitational Redshift on the Casimir Effect in Space," *Mod. Phys. Lett. A*, **30**, 1550159 (2015).

[27] F. Pinto, "If detected, would hypothetical gravitational Casimir effects prove gravity quantization?," *Proc. of the Fourteenth Marcel Grossman Meeting on General Relativity* held in Rome, Italy (2015), to appear; `http://robot.icra.it:8080/publish?publish=on&id=544`.

[28] F. Pinto, "Gravitational Casimir effect, the Lifshitz theory, and the existence of gravitons," *Class. Quantum Grav.*, **33**, 237001 (2016).