Studies in History and Philosophy of Modern Physics 48 (2014) 84–88

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb

Ontological aspects of the Casimir Effect

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ARTICLE INFO

Article history:
Received 24 January 2014
Received in revised form
13 June 2014
Accepted 18 August 2014
Available online 6 September 2014

Keywords:
Casimir Effect
Casimir–Lifshitz forces
Quantum field theory
Macroscopic quantum electrodynamics
Vacuum
Cosmological constant

ABSTRACT

The role of the vacuum, in the Casimir Effect, is a matter of some dispute: the Casimir force has been variously described as a phenomenon resulting “from the alteration, by the boundaries, of the zero-point electromagnetic energy” (Bordag, Mohideen, & Mostepanenko, 2001), or a “van der Waals force between the metal plates” that can be “computed without reference to zero point energies” (Jaffe, 2005). Neither of these descriptions is grounded in a consistently quantum mechanical treatment of matter interacting with the electromagnetic field. However, the Casimir Effect has been canonically described within the framework of macroscopic quantum electrodynamics (Philbin, 2010). On this general account, the force is seen to arise due to the coupling of fluctuating currents to the zero-point radiation, and it is in this restricted sense that the phenomenon requires the existence of zero-point fields. The conflicting descriptions of the Casimir Effect, on the other hand, appear to arise from ontologies in which an unwarranted metaphysical priority is assigned either to the matter or the fields, and this may have a direct bearing on the problem of the cosmological constant.

1. Introduction

The Casimir Effect is an empirically verified quantum mechanical phenomenon involving an attractive force between two parallel uncharged mirrors in vacuum that exists even at zero temperature (Casimir, 1948; Lamoreaux, 1997). It also attracts the interest of philosophers, as the common explanation for the effect appears to make contact with certain metaphysical categories, such as the ontology of the vacuum (Boi, 2011; Saunders, 2002; Saunders & Brown, 1991). But explanations of the phenomenon are not uniformly consistent among theorists. The Casimir force has been described, on the one hand, as an effect resulting from the alteration, by the boundaries, of the zero-point electromagnetic energy (Bordag et al., 2001). On this account, the force is a property of the vacuum and “clear evidence for the existence of vacuum fluctuations” (Carroll, 2001). On the other hand, the Casimir Effect has also been described as a “force [that] originates in the forces between charged particles” that can be “computed without reference to zero point energies”. According to this alternative account, “The Casimir force is simply the (relativistic, retarded) van der Waals force between the metal plates” and the phenomenon offers “no evidence that the zero-point energies are real” (Jaffe, 2005). These descriptions of the Casimir Effect appear to invoke different ontologies in order to account for the phenomenon in question.

Clearly, if the metaphysics of the vacuum is to be informed by the theory of the Casimir Effect, some effort must be made to clarify its requisite ontology. However, popular accounts of the phenomenon involve inadequate ontologies in which an unwarranted metaphysical priority is exchanged between the matter and the fields. Such interpretations are typically grounded in theories that fail to offer a consistently quantum-mechanical description of the interaction of light with macroscopic media. In this author's opinion, the proper locus for interpreting the Casimir Effect is the theory of macroscopic quantum electrodynamics, in which the necessary quantisation of the electromagnetic field and its coupling to bulk materials receives a canonical and consistently quantum-mechanical treatment.

2. Casimir's formula

2.1. Theoretical context

In the standard account of the Casimir Effect, the predicted force occurs between a pair of neutral, parallel conducting plates, separated

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http://dx.doi.org/10.1016/j.shpsb.2014.08.001
1355-2198/

by a distance d, in vacuum at zero temperature. The interaction arises due to a disturbance of the vacuum state of the electromagnetic field (in which there are no real photons between the plates) (Casimir, 1948). This is a quantum effect, as classical electrodynamics does not predict a force at zero temperature.

The prescribed procedure may be summarised as follows (Bordag et al., 2001): take the infinite vacuum energy of quantised electromagnetic field, with Dirichlet boundary conditions imposed on the field modes,

$$E = \frac{1}{2}\sum \hbar\omega, \tag{1}$$

and subtract from it the infinite vacuum energy in free Minkowski space (or with the boundaries infinitely separated), E_∞, having first regularised both quantities $E \to E(\xi), E_\infty \to E_\infty(\xi)$ so that the subtraction procedure is well-defined. Once the difference between the two energies has been computed, the regularisation is removed, $\xi \to 0$, and the result that remains is finite:

$$E_{Casimir} = \lim_{\xi \to 0}[E(\xi) - E_\infty(\xi)]. \tag{2}$$

This is the renormalised Casimir energy, from which we can derive the mechanical force exerted on two parallel plates. For Casimir's case, in which the mirrors are perfectly reflective for all frequencies, we find the pressure force

$$P = -\frac{\hbar c \pi^2}{240 d^4}. \tag{3}$$

As an aside, we should observe that nobody follows this recipe exactly for the electromagnetic field, though it has been pedagogically applied to a 1d scalar field where the calculation is somewhat simpler (Bordag et al., 2001). If we attempt to follow the prescribed procedure precisely, applying a frequency cutoff term $\exp(-\xi\omega/c)$ as the regulariser, we discover an additional divergent term that is not removed by subtracting the so-called background energy (Horsley & Simpson, 2013); it appears to correspond to waves running parallel to the plates. Admittedly, it does not contribute to the force in this case, though it cannot be ignored in other cases (Simpson, Horsley, & Leonhardt, 2013). Typically it disappears in the course of applying the Euler–MacLaurin formula (e.g. Boi, 2011; Leonhardt, 2010; Milonni, 1994). Suffice it to say that the simple picture of taking the difference between two energies can be somewhat misleading.

2.2. Physical interpretation

Nevertheless, considered on the basis of an energy mode summation, as employed by Casimir (1948), it seems that the quantised electromagnetic field in its ground-state, with 'external boundary conditions', is sufficient to determine a force – an almost matter-free prescription for obtaining the phenomenon in which the boundary conditions become simply topological features of the space (Boi, 2011). Casimir's formula, depending solely upon the constants $\hbar$ and c and the distance d between the plates, serves to consolidate this impression.

But this interpretation is naive. The vacuum energy, as we have observed, is infinite, and in addition to imposing boundary conditions on the field we must apply some kind of regularisation to tame the mode summation and permit the subtraction of diverging terms. Although the various techniques employed to do this often serve to obscure the fact, it is in the procedure of regularisation that some of the properties of matter (in particular, its dispersive behaviour) are permitted to leak into the calculation, albeit rather crudely (Horsley & Simpson, 2013). Significantly, it is not possible to extract anything meaningful (or measurable) about the Casimir force until they are permitted to do so. Furthermore, when we relax the highly artificial boundary condition of perfect mirrors, as we must in order to predict the Casimir Effect in real materials, we are forced to sum contributions to the Casimir energy over a dispersive material response across the whole mode spectrum, substantially modifying the predicted force.[1] To do this kind of calculation, however, we must abandon the mode summation and adopt a more sophisticated apparatus, like Lifshitz theory. Casimir's result can still be recovered, but only as a limiting case (Leonhardt, 2010).

3. Lifshitz theory

3.1. Theoretical context

Lifshitz theory has proven an important benchmark for the prediction of Casimir forces in more realistic cases, enjoying significant experimental verification (Munday, Capasso, & Parsegian, 2009; Rodriguez, Capasso, & Johnson, 2011). In the context of Lifshitz theory, the Casimir Effect is a result of fluctuating current densities in the two plates (Dzyaloshinskii, Lifshitz, & Pitaevskii, 1961; Lifshitz, 1955; Lifshitz & Pitaevskii, 2003). A force arises from the interaction of the currents through the electromagnetic field that they generate in the cavity. The plates are now treated more realistically as dielectric with frequency-dependent permittivities and permeabilities, and this substantially affects both the size (and, in some cases, the nature[2]) of the predicted force.

The formalism is written in terms of the electromagnetic Green function, which describes the field produced by sources of current within the system. A stress tensor σ is written in terms of this Green function, from which a force can be derived. The stress tensor, however, like the zero-point energy, contains a divergent contribution that must also be regularised.[3] Typically this is achieved through subtracting a stress calculated using an auxiliary Green function associated with an infinite homogeneous medium σ_0 (Leonhardt, 2010; Lifshitz & Pitaevskii, 2003; Philbin, 2011; Philbin, Xiong, & Leonhardt, 2009; Pitaevskii, 2011), and computing the physical stress in the limit of the point of measurement approaching a point source:

$$\sigma_{Casimir} = \lim_{\mathbf{r}' \to \mathbf{r}}[\sigma(\mathbf{r}, \mathbf{r}') - \sigma_0(\mathbf{r}, \mathbf{r}')]. \tag{4}$$

One can then compute a finite stress tensor for the system that depends on the dielectric functions of the material at imaginary frequencies (quantities obtained from the dielectric properties for real frequencies by Hilbert transformation). Only then can the force be derived. Both Casimir's and Lifshitz' regularisations give identical results in the limiting case of a cavity sandwiched between perfectly reflecting mirrors (Leonhardt, 2010), which does not exist in nature, but the stress tensor also offers measurable predictions for realistic systems at finite temperatures.

[1] Jaffe (2005) correctly points out that Casimir's formula (3) can be recovered 'without mentioning vacuum energies', but confusingly claims that (3) has been 'measured to about 1% precision'. This is not the force that Lamoreaux measured (Lamoreaux, 1997), and claims to accuracies of this order are questionable (Lamoreaux, 2011). The more significant object is the general stress tensor from Lifshitz theory, and the more interesting question pertains to the circumstances of its derivation. (The need for 'finite conductivity corrections' to Casimir's result, however, are acknowledged later in Jaffe, 2005.)

[2] Lifshitz theory predicts repulsive Casimir forces, under certain circumstances (Capasso & Munday, 2011).

[3] Additional divergences in the stress appear in the generalisation to inhomogeneous media (where the optical properties vary continuously along at least one spatial axis). In this case, the regularisation cannot remove the infinities; it appears that the spatially dispersive nature of the material must be taken into account (Horsley & Simpson, 2013; Leonhardt & Simpson, 2011; Simpson, 2013; Simpson et al., 2013).