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Retardation turns the van der Waals attraction into a Casimir repulsion as close as 3 nm

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Casimir forces between surfaces immersed in bromobenzene have recently been measured by Munday et al. [Nature (London) 454, 07610 (2009)]. Attractive Casimir forces were found between gold surfaces. The forces were repulsive between gold and silica surfaces. We show the repulsion is due to retardation effects. The van der Waals interaction is attractive at all separations. The retardation-driven repulsion sets in at around 3 nm. To our knowledge, retardation effects have never been found at such a small distance before. Retardation effects are usually associated with large distances.

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When two objects are brought together, correlations in fluctuations of the charge and current densities in the objects or fluctuations of the fields usually result in an attractive force (retardation effects) and the result is the Casimir force [2,8]. By retardation effects, we mean all effects that appear because of the finite speed of light, not just the reduction in correlation between the charge density fluctuations at large distances; new propagating solutions to Maxwell’s equations appear that bring correlations between current density fluctuations. When these propagating modes dominate, we call the force Casimir force; when the surface modes [7] dominate, we call the force van der Waals force.' The classical literature says that retardation is due to the finite speed of light that weakens the correlations. This is misleading. It is due to the quantum nature of light [11,12]; this becomes obvious at the large separation limit where the weakening is independent of the speed of light.

Since the famous experiments of Deryaguin and Abrikossova [13], there has been much interest in phenomena which measure the van der Waals forces acting between macroscopic bodies. The early experiments which measured the forces between quartz and metal plates covered only the retarded region. The experiments of Tabor and Winterton [14] and subsequently of Israelachvili and Tabor [15,16] fitted the retarded region. The experiments of Tabor and Winterton [14] and subsequently of Israelachvili and Tabor [15,16] fitted the retarded region. The forces were repulsive between quartz and metal plates covered only the retarded region. The experiments of Tabor and Winterton [14] and subsequently of Israelachvili and Tabor [15,16] fitted the retarded region. The forces were repulsive between quartz and metal plates covered only the retarded region. The experiments of Tabor and Winterton [14] and subsequently of Israelachvili and Tabor [15,16] fitted the retarded region. The forces were repulsive between quartz and metal plates covered only the retarded region. The experiments of Tabor and Winterton [14] and subsequently of Israelachvili and Tabor [15,16] fitted the retarded region. The forces were repulsive between quartz and metal plates covered only the retarded region. The experiments of Tabor and Winterton [14] and subsequently of Israelachvili and Tabor [15,16] fitted the retarded region. The forces were repulsive between quartz and metal plates covered only the retarded region. The experiments of Tabor and Winterton [14] and subsequently of Israelachvili and Tabor [15,16] fitted the retarded region. The forces were repulsive between quartz and metal plates covered only the retarded region. The experiments of Tabor and Winterton [14] and subsequently of Israelachvili and Tabor [15,16] fitted the retarded region. The forces were repulsive between quartz and metal plates covered only the retarded region. The experiments of Tabor and Winterton [14] and subsequently of Israelachvili and Tabor [15,16] fitted the retarded region. The forces were repulsive between quartz and metal plates covered only the retarded region. The experiments of Tabor and Winterton [14] and subsequently of Israelachvili and Tabor [15,16] fitted the retarded region. The forces were repulsive between quartz and metal plates covered only the retarded region. The experiments of Tabor and Winterton [14] and subsequently of Israelachvili and Tabor [15,16] fitted the retarded region. The forces were repulsive between quartz and metal plates covered only the retarded region. The experiments of Tabor and Winterton [14] and subsequently of Israelachvili and Tabor [15,16] fitted the retarded region. The forces were repulsive between quartz and metal plates covered only the retarded region.
electric (TE), \( g(\omega_n) = g^{TM}(\omega_n) + g^{TE}(\omega_n), \) where

\[
g^{TM}(\omega_n) = \frac{1}{\beta} \int \frac{d^2q}{(2\pi)^2} \ln \left\{ 1 - e^{-2\pi d} \left[ \frac{\varepsilon_1 (i\omega_n) \gamma_2 - \varepsilon_2 (i\omega_n) \gamma_1}{\varepsilon_1 (i\omega_n) \gamma_2 + \varepsilon_2 (i\omega_n) \gamma_1} \right] \right\};
\]

\[
g^{TE}(\omega_n) = \frac{1}{\beta} \int \frac{d^2q}{(2\pi)^2} \ln \left\{ 1 - e^{-2\pi d} \left[ \frac{\gamma_2 - \gamma_1}{\gamma_2 + \gamma_1} \right] \right\};
\]

\[
\gamma_1 = \sqrt{q^2 - \varepsilon_i(i\omega_n)/(i\omega_n/c)^2}.
\]

In the nonretarded treatments, there are no TE contributions, and the result is

\[
g(\omega_n) = \frac{1}{\beta} \int \frac{d^2q}{(2\pi)^2} \ln \left\{ 1 - e^{-2\pi d} \left[ \frac{\varepsilon_1 (i\omega_n) - \varepsilon_2 (i\omega_n)}{\varepsilon_1 (i\omega_n) + \varepsilon_2 (i\omega_n)} \right] \right\}.
\]

Fig. 3, there is a transition region between the van der Waals region (where retardation does not influence the result) and the long-range Casimir region. In this region, the retarded Casimir energy is attractive. This means that it is possible via the optical properties to tune the materials used such that in one region they give attractive Casimir interactions and in another region they give repulsive Casimir interactions. There is also a maximum of the repulsive Casimir interaction, to our knowledge not yet experimentally observed. This maximum (which occurs around \( d = 5 \) nm) and the transition from attraction to repulsion (which occurs around \( d = 3 \) nm) pose suitable experimental tests for the validity of the theory. Notably the contributions from transverse magnetic modes are zero around approximately 26 Å. This means that at one very short separation the Casimir force comes entirely from transverse electric modes. These modes are absent if retardation is neglected. This is a consequence of the total force in the system being very small. Our results suggest that it is possible to measure retardation effects at much shorter separations than has previously been expected. Experiments are often performed in the sphere-plate geometry. Then the force in terms of the Casimir free energy, \( F(d) \), is [26] \( 2\pi RF(d) \), where we see that the force is proportional to the energy; the maximum repulsive force occurs at the position of the maximum repulsive energy. The attractive Casimir energy between gold surfaces in either bromobenzene or air is shown.

**Fig. 1.** (Color online) The dielectric function at imaginary frequencies for SiO\(_2\) (silica) [24], Bb (bromobenzene) [23], and Au (gold) [25].

**Fig. 2.** (Color online) The spectral function, \( g(\omega_n) \), as a function of imaginary frequencies for two different separations.
in Fig. 4. Here both the retarded and nonretarded energies decrease monotonically with separation.

The long-range part of the interaction is shown in Fig. 5. In the 1- to 2-μm range, the thermal entropic effect starts to become important. This is similar to what we found for the Casimir force between real metal surfaces in a vacuum [25].

Using optical measurements on the interacting objects and liquid makes it possible to predict the force—from short-range attractive Casimir force to long-range repulsive Casimir force. We find similar effects of retardation when gold is replaced with silver (the difference is that the crossing from attractive Casimir interaction free energy between two gold surfaces in either (a) bromobenzene or (b) air.

We predict strong retardation effects that are much more pronounced at short and intermediate separations in systems with repulsive Casimir interaction as compared to in systems with attractive Casimir interaction. We stress that it should be possible to measure a maximum repulsive Casimir force. We suggest that this distance of maximal repulsion should be the optimal distance to enable quantum levitation of nanoscale devices (floating on each other in a liquid due to repulsive Casimir interaction). The essential physical parameter is \( \epsilon(\omega_n) \), a real and positive quantity intimately connected with absorption (imaginary permittivity \( \epsilon'' \)) through the Kramers-Kronig dispersion relation

\[
\epsilon(\omega_n) - 1 = \frac{2}{\pi} \int_0^\infty \frac{x\epsilon''(x)}{x^2 + \omega_n^2} \, dx.
\]

From this perspective, it is thus the coupling within the system to a frequency-dependent heat bath, rather than the finite speed of light, which is important. Repulsive Lifshitz forces were found a long time ago in indirect-force measurements. One example is the work of Anderson and Sabiski on films of liquid helium on calcium fluoride and similar molecularly smooth surfaces [30]. The films ranged from 10 to 200 Å [30]. The thickness of the films could be measured to within a few percent in most cases. For the saturated-film measurements, the repulsive van der Waals potential was equal to the negative of the gravitational potential [30]. Good agreement was found [21] between these experimental data and the results from Lifshitz theory. In another more subtle experiment, Hauxwell and Ottewill [31] measured the thickness of films of oil on water near the alkane saturated vapor pressure. For this
system, n-alkanes up to octane spread on water. Higher alkanes do not spread. It is an asymmetric system (oil-water-air), and the surfaces are molecularly smooth. The phenomenon depends on a balance of van der Waals forces against the vapor pressure [22,31,32]. The net force as a function of film thickness depends on the dielectric properties of the oils. As demonstrated [22], it involves an intricate balance of repulsive and attractive components from different frequency regimes. When the ultraviolet and visible components are repulsive and attractive components from different frequency optical frequencies, the permittivity for ice exceeds that of water for frequencies higher than about 2 × 10^{16} \text{rad/s}. A thin layer of water at first tends to thicken, but the thickening is gradually hampered because of the retardation. The surface melting is thus incomplete. One notices from Fig. 1 in [33] that the crossing point between the permittivities for ice and water occurs at about 1.5 × 10^{15} \text{rad/s}, about the same point as the crossing point in our Fig. 1.

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