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The Nuclear Force Computed as the Casimir Effect Between Spheres

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The purpose of this paper is to investigate the possibility that the Casimir effect, normally very weak, is strong enough to be significant on the scale of nuclear forces around 1 femtometer (fm). Computations were performed for the Casimir effect between two spheres using a proximity force approximation. It was found that at 2.7 fm the computed Casimir force is strong enough to overcome Coulomb repulsion and at 0.7 fm it is approximately 32 times stronger than Coulomb repulsion. These values indicate that this strong Casimir force is important on scales of distance consistent with the nuclear force. With refinement it appears likely that the strong Casimir force can account for the nuclear force in its entirety, allowing unification of the nuclear force with quantum electrodynamic theory.

1. Background

The Casimir effect was discovered by Casimir and Polder and first published in Nature in 1948 and titled "The Influence of Retardation on the London-van der Waals Forces."[1] The theory is based on the idea that vacuum fluctuations can be considered to behave as induced dipoles, producing a London-van der Waals force.

What Casimir proposed is if two plates were brought very close together, certain wavelengths would be excluded from the cavity between the plates, thus causing pressure on the plates due to the van der Waals forces produced by vacuum fluctuations to be reduced.

The reduction in force then leads to a pressure differential where the pressure pushing the plates together overcomes the pressure pushing them apart, so that the plates are pushed together unless otherwise constrained. In the late 1990s the effect was measured to a good degree of precision confirming the theory.[2][3]

2. Investigation

While the Casimir effect has a very small magnitude when measured over scales in the 0.1 to 1 micron range, the force generally varies with the inverse of distance to the fourth power. Consequently, it becomes much stronger over very small distances, such as the space between nucleons. A search of the Internet revealed a paper by Ardeshir Mehta, which contained a simple computation of the Casimir effect at 1 fm, using Equation 1.[4] He obtained a value of F = 1040 Newtons (N) showing that the Casimir force was almost 33 times the Coulomb repulsion at 1 fm.

Equation 1

$$F = -\frac{\hbar c \pi^2}{240x}\frac{A}{L^4}$$

Equation 1 is the standard Casimir force equation for two flat plates of area ***A*** and distance ***L*** between them to which Mehta added a modifier ***x***. He arbitrarily assigned a value of ***x*** = 5 in order to correct for the curvature of the nucleons. It has been rewritten here slightly for consistency. The negative sign indicates that the force is attractive.

Equation 2

$$E = -\frac{\hbar c \pi^2}{1440}\frac{\pi a^2}{L^2(2a+L)}$$

Given the closeness of this approximation, the author decided to perform the same computation using a Proximity Force Approximation (PFA) equation for two spheres. A PFA equation for two spheres can be found in Appendix A of a paper by Aurel Bulgac et. al.[5] Their energy equation for two spheres with a common radius ***a*** and minimum distance between them ***L*** is shown in Equation 2.

We can note that $\boldsymbol{a}$ is the radius of the proton. The 2010 CODATA value for the radius of the proton, 0.8775(51) x 10^{-15} m, was used in all calculations as radius $\boldsymbol{a}$. Note that this equation is likely not ideal for the case where $\boldsymbol{L}$ is greater than or equal to $\boldsymbol{a}$, so the results that follow are best considered as a first approximation.

The simplest way to compute the force from equation 2 is to first compute the energy for each distance $\boldsymbol{L}$, and then compute the force for each distance. Those results can then be compared to the Coulomb repulsive force computed using the standard equation shown as Equation 3.

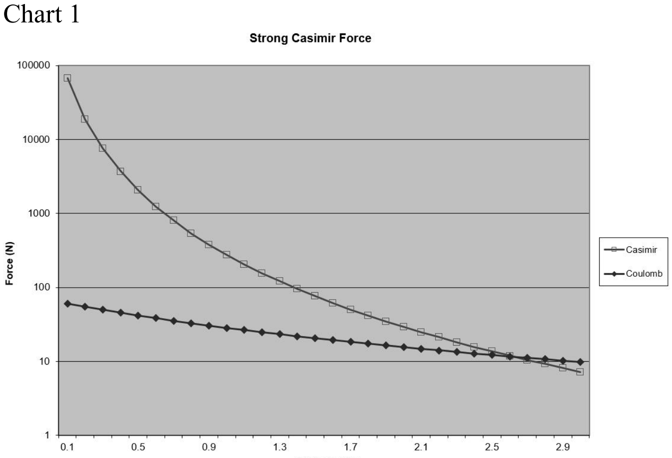
Equation 3

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q^2}{r^2}$$

3. Computation

The Casimir force was calculated for minimum approach distances $\boldsymbol{L}$ between spheres in 0.1 fm increments from 0.2 fm to 3 fm. The Coulomb repulsion was also computed using the proton's electric charge and the distance between the centers of the protons based on the same distance $\boldsymbol{L}$. The data was plotted with a logarithmic Y scale given the rapid change in the Casimir force for distances less than 1 fm. The results are shown in Chart 1.

Chart 1



At 3 fm the Casimir force is 8.1 N while the Coulomb force is 10.2 N. At 2.7 fm the Casimir force strengthens to 11.9 N overtaking the Coulomb repulsion at 11.6 N. As the nucleons approach 2 fm the Casimir force reaches 34.8 N while the Coulomb repulsion is only 16.4 N, and at 1 fm the opposing forces are 379 N and 30.5 N respectively with the Casimir force now 12.4 times stronger.

By the time the nucleons are within 0.5 fm, the Casimir force is 3707 N while the Coulomb repulsion is 45.6 N so the Casimir force is 81 times stronger. The values for this strong Casimir force based on the PFA are consistent with the known strengths and distances of the nuclear force.

The strong Casimir force calculations do, however, show an exponential increase as the two nucleons continue to approach, reaching 66,800 N at 0.2 fm, which would be similar to the gravitational attraction of a proton sized black hole if that were true. That means that either the Casimir force is somehow diminished at close range, or there is an even stronger repulsive force, or both.

It is known that two protons cannot occupy the same state, including position, as that is required by the Pauli exclusion principle. The force underlying the Pauli exclusion principle is, however, still unknown. But that force is known to be responsible for the existence of proton degeneracy pressure and neutron degeneracy pressure which is important in white dwarfs and neutron stars. So, at some point we must expect that degeneracy pressure overcomes Casimir attraction between protons and protons, neutrons and neutrons and also, importantly, protons and neutrons.

4. Discussion

The nuclear force has long been considered to be due to particle exchange since Yukawa first described it that way in 1935.[6] After pions where discovered this exchange was said to be due to the exchange of neutral pions. A single pion exchange event was not, however, adequate to describe the interaction in its entirety, especially not the repulsive force at small distances. So additional exchanges where theorized such as two pion and omega particle exchanges.

With the advent of quark theory these exchanges were thought to be meson exchanges where the mesons where composed of quarks. Some have proposed that gluons may also play a role. A neutral pion is said to be composed of the quark arrangement specified in Equation 4.

Equation 4

$$\pi^0 = \frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$$

It is not clear how up and antiup and down and antidown quarks combine without annihilating immediately, since they are not known to combine in a metastable resonant state. And it is also not clear how a fundamental particle could be subtracted from another fundamental particle or how a fundamental particle can be divisible by the square root of two.

With the strong Casimir force having approximately the same range and strength as the nuclear force between 0.5 fm and 3 fm, that puts us in a bit of a quandary. It is highly unlikely that there are two separate forces with the same range and strength that are responsible for the same force interaction.

The strong Casimir force is firstly based on London-van der Waals forces, which are well known. Secondly, the Casimir effect has been proven experimentally at the micron range, so its existence cannot be dismissed. There is no known mechanism by which the Casimir effect could be thought not to act at the fm distance range. If a particle has charge and can scatter other particles, which a proton can, it will participate in the Casimir effect.

Probably the most important point in favor of the strong Casimir force model is that the Casimir effect is part of quantum electrodynamic theory so the nuclear force is not a separate force and can be unified with electromagnetic force theory.

5. Conclusion

While the Casimir effect is usually thought of as a very weak force, computations show that it becomes very strong at distances of a few fm or less. This is due to the force strengthening to the fourth power of the distance. This strong Casimir force is consistent with the known magnitude and distances associated with the nuclear force between nucleons within the atomic nucleus.

While the computations here show a strength somewhat below the known values, it is expected that more precise computations, including the van der Waals attraction over the entire particle volume, will yield a better result. It is also necessary that these computations be based on an equation which is valid in situations where L is equal to or greater than a.

The question is then, that given we have both a particle exchange model and a strong Casimir force model to explain the nuclear force, whether we should discard one in favor of the other or somehow combine the two? It seems unlikely that there are redundant force mechanisms in nature responsible for the same force and force magnitude, so the combination solution should be rejected.

The particle exchange model for the nuclear force certainly has time in its favor, as all physicists are indoctrinated into that theory. That said, the physical interaction responsible for an attractive force in a particle exchange model has never been well explained.

On the other hand, the Casimir effect, as a London-van der Waals force, has a strong fundamental basis, both theoretical and experimental, so it cannot be dismissed. The Casimir effect is also the simpler and more elegant of the two solutions, while providing a physical basis for explaining attraction. And it ultimately allows us to unify the nuclear force with electromagnetic theory, thus reducing the number of fundamental forces. We must therefore conclude that the nuclear force is the strong Casimir force.

Note: This paper was edited to correct errors, add clarifications, and remove confusing or speculative information that was in the original 2014 version.

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