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Quantum field energy sensor based on the Casimir effect

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Abstract

The Casimir effect converts vacuum fluctuations into a measurable force. Some new energy technologies aim to utilize these vacuum fluctuations in commonly used forms of energy like electricity or mechanical motion. In order to study these energy technologies it is helpful to have sensors for the energy density of vacuum fluctuations. In today's scientific instrumentation and scanning microscope technologies there are several common methods to measure sub-nano Newton forces. While the commercial atomic force microscopes (AFM) mostly work with silicon cantilevers, there are a large number of reports on the use of quartz tuning forks to get high-resolution force measurements or to create new force sensors. Both methods have certain advantages and disadvantages over the other. In this report the two methods are described and compared towards their usability for Casimir force measurements. Furthermore a design for a quantum field energy sensor based on the Casimir force measurement will be described. In addition some general considerations on extracting energy from vacuum fluctuations will be given.

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1. Introduction

One of the most fascinating effects in Quantum field theory is the Casimir effect, which leads from microscopic fluctuations to a macroscopic force [1]. In 1948 Hendrik Casimir came to the conclusion that two parallel metal plates should experience an attractive force. Since there are less quantum states between the plates than there are outside the plates, there should be a difference in photon pressure that

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leads to a force on the plates. The effect is also closely related to the van der Waals forces [2]. In fact Casimir found his result while working on discrepancies of van der Waals forces. After the theoretical prediction Sparnaay made the first measurements in 1958 and van Blokland in 1978. The early experiments had large uncertainties.

Up to the late 1990´s the work on the Casimir effect was mostly theoretical [3]. The recent expansion of experimental work on the Casimir effect was started with the groundbreaking work of Lamoreaux [4] and Umar Mohideen [5]. The later experiments use state of the art nanopositioning with piezo actuators. Umar Mohideen uses the well known force measurement techniques that are used in atomic force microscopy. An overview of recent experimental developments can be found in Onofrio's publication [6] and in the review article of Mostepanenko [7].

The motivation for this work in setting up a Casimir force sensor lies in the fact that we still do not have sufficient experimental data on the influence of material and geometries, i. e., boundary conditions, on the energy of the vacuum state. So the shape of the objects bordering the space or being in the space in question is of interest as well as the properties of the materials involved.

While designing the measuring apparatus for the Casimir force measurements it was brought to the attention of the author by solid state physicist Bert Rähmer that there is an alternative force measuring technique in experimental atomic force microscopy utilizing commercially available quartz crystal frequency standards [8]. A survey of the current literature on force measuring techniques made it clear that the quartz tuning fork usually employed in the watch industry for time measurements is widely used to measure sub-nanonewton and piconewton forces, see figure 1. The quartz tuning fork is a highly developed and thoroughly engineered precision instrument. The watch industry produces billons of these tuning forks each year. The most used frequency is 2^{15} =32768 Hz. To achieve quality factors of ~10^5 the crystal orientation and manufacturing process need to be of high standard. The quartz tuning fork is currently used for measuring shear forces in scanning near field optical microscopy (SNOM) [9] and to measure normal forces in magnetic force microscopy [10], in atomic point contact measurements [11], and for seismometers and micro gyros as accelerometers [12]. The large amount of available literature is very helpful in designing the apparatus for Casimir force measurements. Grober et al. discuss the fundamental limits of force detection using quartz tuning forks. Grober found that at room temperature, pressure and atmosphere, the noise level of his tuning fork was 0.62 pN / $Hz^{1/2}$ and shows a root mean square motion of 0.32 pm [13]. Karrai has also published a review paper about the basic operation of a quartz tuning fork as a shear and friction force sensor, which covers most of the essential topics like oscillation model, spring constant, signal detection and noise [14]. Giessibl, who is credited to be the first to show atomic resolution with noncontact AFM, has published on the understanding of the physical relationship between the frequency shift of the tuning fork and the applied force [15]. The conversion of the frequency shift signal into a force value is of high importance in the application of quartz tuning forks in Casimir force measurements.

Rensen at al compared the resolution of force sensing with quartz tuning forks and light silicon cantilevers [16]. The motivation for setting up the quartz tuning fork was that the resolution of the tuning fork is higher compared with silicon cantilevers. In addition the tuning fork is self-sensing and the measuring only needs electronic parts and is supposed to be more robust and cost-effective than the optical laser reflection used in the light silicon cantilever setup. The tuning fork is also very suitable for low temperature force measurements because of the low energy dissipation of the fork, as low as picowatts, and the removal of optical dealignment problems on cooling down [17].

Figure 1. Quartz tuning fork, in capsule and with opened package

Hence it seems promising to use quartz tuning forks for Casimir measurements as they are inexpensive, self-sensing, have no need for laser and optics, are easy to operate in vacuum and are robust and stiff, while being sensitive enough for Casimir forces.

Nomenclature

Q	quality of a resonance
F	force (N)
k	spring constant (N/m)
f	frequency (Hz)
R	radius (m)
x	distance (m)
E	Young module (N/m^2)
W	width (m)
T	thickness (m)
L	length (m)
d	separation of Casimir plates (m)

2. Force measurements

The measurement of sub-nanonewton forces is a central part of the atomic force microscope. The standard method for force sensing in the AFM is to use light silicon cantilevers with spring constants of 40 to 0.01 N/m. So this method is described first, followed by the force measurement based on quartz tuning forks.

2.1. Light silicon cantilevers

The method described here is known as "contact mode" in the AFM terminology. In this configuration the force is measured by the deflection of the tip of the cantilever as seen in figure 2. In order to measure sub-nanonewton forces, typical interatomic tip sample forces, the silicon cantilever needs to be thin (so called light), typically just less than 1 micro meter. To measure the deflection a laser beam is reflected from the tip onto a field of photodiodes. The difference of the photodiodes A and B is the signal that is proportional to the force on the cantilever. The relationship between the small deflection Δz and the force is known as Hooke's law : $F= k\, \Delta z$. Typical spring constants k are 40 to 0.01 N/m. To convert the signal from the photodiodes into a force, the spring constant of the cantilever needs to be known. There are several ways to measure the spring constant of the cantilever. Either a known force needs to be applied to calibrate the spring constant statically or to calibrate the cantilever dynamically a known weight m needs to be attached to the cantilever. In our case the sphere can be used as a known mass. Then the frequency f is related to the spring constant and the mass $f = (k/m)^{1/2}$. The spring constant can be calculated by measuring the frequency. More details of this technique can be found in Mohideen's publications [5].

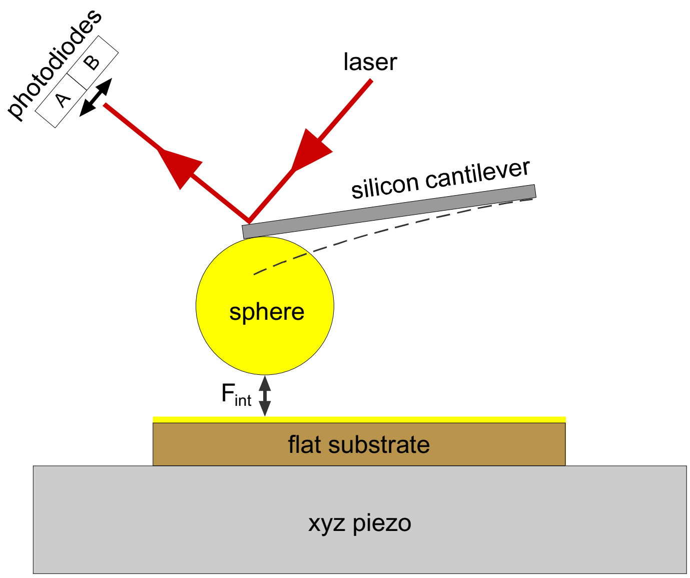

Figure 2. Basic principle of measuring force with a cantilever and bounced laser beam

The sensitivity of the AFM is governed by the noise in the photodiode signal. The noise has its origin in physical vibrations of the cantilever tip and the electrical noise from the photodiodes and the rest of the electronics. In our AFM the noise level is 1.5 mV. The photodiode signal is converted into force by multiplying the signal with a signal-to-displacement factor and the spring constant that converts the nm length into a force in Newton. The signal-to-displacement factor depends on the reflectivity and reflection area of the cantilever tip and the locus of reflection on the cantilever. In a typical case the conversion factor is .5 to 2 mV/nm. Lowest spring constant for cantilevers with sphere and gold coating was 0.05 N/m leading to a sensitivity of 37 pN at best. A desired spring constant of 0.01 N/m would lead to a sensitivity of 7.5 pN.

2.2. Quartz tuning forks

The force measurement with quartz tuning forks is based on the frequency shift that occurs if a force is applied to the tuning fork when it is operated close to its resonance frequency. The piezoelectric effect of the quartz crystal yields an electric signal proportional to the deformation. The tuning fork can be driven by applying an AC voltage directly to the electrodes of the tuning fork. A simple model for the tuning fork is a driven harmonic oscillator. The response to a driving frequency is well known. The amplitude and phase response is shown in figure 3.

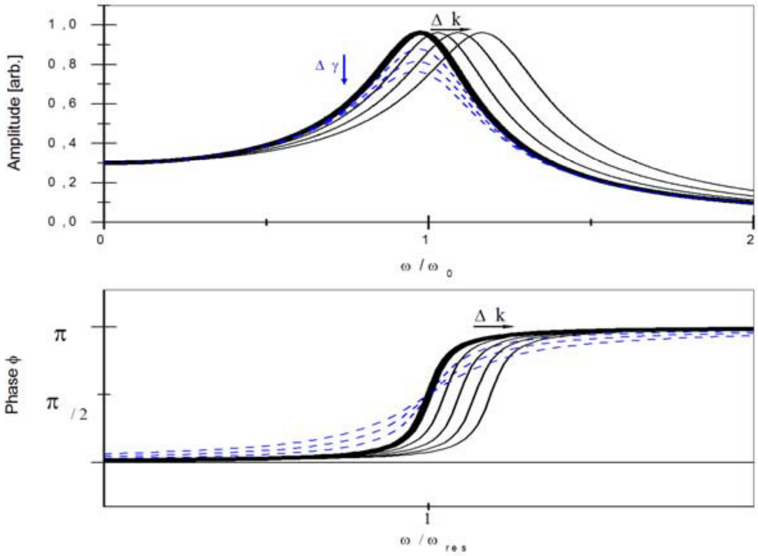

Figure 3. Amplitude and phase of driven harmonic oscillator with effect of rising spring constant k (solid lines) and damping γ (dashed lines)

In our case the external force has to be included in the equation. The external force can be treated as a change of the spring constant of the system. The result is shown in figure 3. The resonance frequency is shifted when an external force is applied (Δk). It can also be suitable to track the phase difference between the driving force and the system because at the resonance frequency the gradient of the phase ϕ is much larger than the gradient of the amplitude.

The shift of the resonance frequency f_0 is related to the derivative of the force on the tuning force.

$$\Delta f \approx \frac{f_0}{2k}\frac{\partial F}{\partial x} \tag{1}$$

Much more details can be found in the AFM literature under the keyword „dynamic mode theory". An important value of the resonance is the quality Q. The quality of a resonance is known as the frequency f divided by the full width at half maximum (FWHM).

$$Q = f / FWHM \tag{2}$$

The physical amplitude of the tuning fork displacement has to be small in relation to the desired position resolution. We need a quasi static regime in order to make Casmir measurements, as the position resolution should be of a few nm. The displacement of the tuning fork arms has been studied by several authors. If the driving voltage is sufficiently small the displacement is less than a few nm and can be as low as pm [10, 19].

A simple formula for Casimir force in flat sphere geometry (figure 2) is

$$F = -\frac{\pi^3 \hbar c}{360}\frac{R}{x^3} \tag{3}$$

R is the radius of the sphere and x is the distance between the flat surface of the tuning fork and the sphere. If we use formula (1) with the force relationship (3) we find the expected frequency shift

$$\Delta f \approx \frac{3 f_0}{2k}\frac{\pi^3 \hbar c}{360}\frac{R}{x^4} \tag{4}$$

The spring constant k can be calculated by measuring the physical dimensions of the tuning fork. The spring constant is given by

$$k = \frac{E}{4} W \left(\frac{T}{L}\right)^3 \tag{5}$$

E is the Young module. For quartz crystal E is

$$E = 7{,}87 \cdot 10^{10}\ N / m^2 \tag{6}$$

L is the length, W the width and T the thickness of the tuning fork [9].

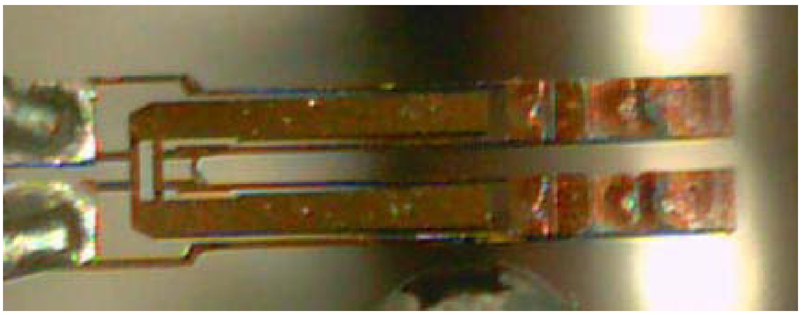

Figure 4. Quartz tuning fork and metal ball

The sensitivity of our tuning fork measuring system is governed by the sensitivity of the frequency measurement. In our case a change of 1 mHz can be detected. As can be seen in formula (4) the frequency shift is proportional to the frequency and the radius of the sphere. Since the frequency is fixed to 32765 Hz it is desirable to have a large radius and a low spring constant k.

In theory 100 kHz tuning forks would lead to a higher signal, but they have a very high k and are therefore unsuitable. Furthermore the sphere should be as large as possible and the spring constant should be as low as possible. Larger spheres would give a higher signal but they are more difficult to place and align.

3. Casimir force measurement with quartz tuning fork and Anfatec AFM

To measure the Casimir force and the surface roughness of the samples a standard level AFM from Anfatec was used. The AFM consist of a head, a body, the control electronics and a pc. The head includes the silicon cantilever, the laser and the photodiodes as well as x-y positioning for the laser and the photodiodes. The body includes the xyz piezo scanner and 3 stepper motors for coarse approach as seen in figure 5.

The software allows to make approach curves. In this case the photodiode signal is measured versus the z displacement. From the current position the z, which is the distance from the cantilever tip or sphere to the surface of the substrate, is varied to a set distance and back. Both directions are recorded.

For the Casimir measurements a micro sphere from Duke Scientific with a diameter of 201 microns is glued to the cantilever with silver loaded epoxy. So far we used cantilevers from MikroMasch, triangle CSC11-A with 0,35 N/m, tipless cantilever CSC12-E and Veeco MLCT-AUMN. After the ball is glued to the cantilever, the whole arrangement is coated with a gold layer of several 100 nm thickness [20].

Figure 5.AFM with standard head and optical positioning aid

The limiting factor for sensitivity is the electric noise in the photodiode signal. Under good conditions the noise is 1.5 mV. A good signal strength is about 2000 mV. An important value is the conversion factor from photodiode mV signal into nm displacement of the cantilever. If the spring constant is known the force can be calculated. Typical conversion factors were .5 to 2 mV/nm. With a spring constant of 0.03 N/m this leads to a sensitivity of 45 pN. Estimation of k by measuring the resonance frequency and using the calculated weight of the micro sphere leads to a value of 0.05 N/m.

In order to design a more compact and robust Casimir force measurement setup that can be used as a sensor in the field to measure variation in the Casimir force the silicon cantilever was replaced with a quartz tuning fork. To study the behavior of the tuning fork, a new AFM-Head was designed that integrated the tuning fork into the existing Anfatec AFM, see figure 6.

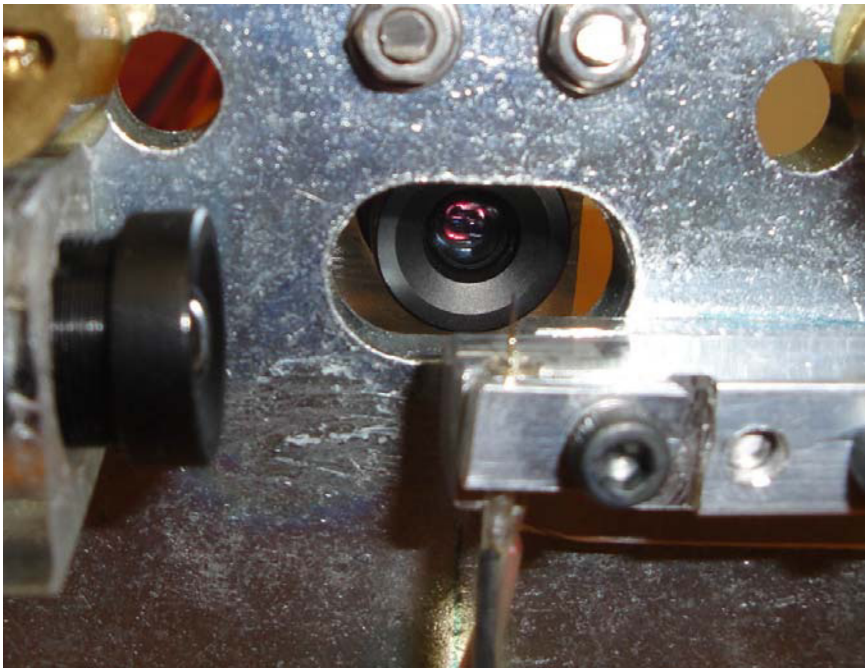

Figure 6. New AFM head with holding structure for the tuning fork and cameras as a positioning aid

The tuning fork is driven by a function generator from the Anfatec lock-in card. The driving voltage is constant and can be varied. The lowest possible strength of 10 mV is used. The voltage is applied between ground and the electrode of the tuning fork. The other electrode is connected to the input of the Anfatec lock-in card. A PC with the Anfatec program is used to read out the value from the lock-in. The program also scans through the frequency in a preset band in order to record resonance curves as shown in figure 7 and figure 8. The time constant of the lock-in was varied between 500 ms and 50 ms.

In figure 7 a resulting resonance of the tuning fork is shown. The quality Q is 4.6 10^4.

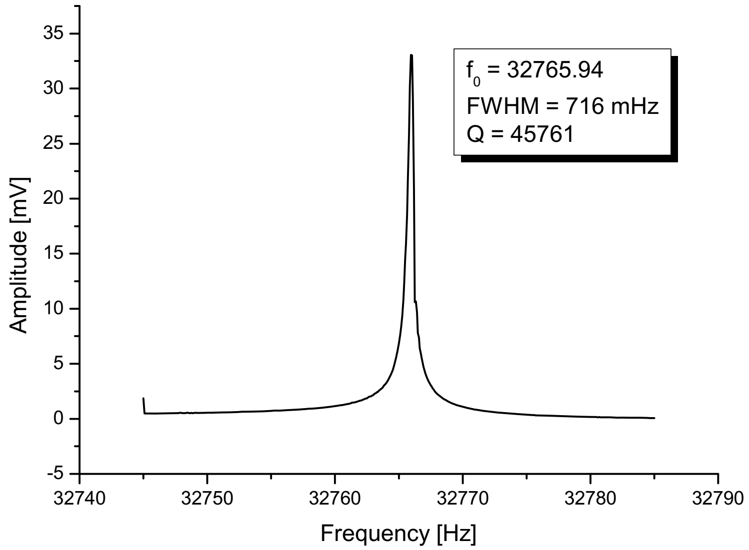

Figure 7. Resonance of the quartz tuning fork in vacuum.

In order to conduct Casimir force measurements the long-term stability is important. The drift in resonance frequency was measured to less than 4 mHz in 12 hours. The result is shown in figure 8. The drift was recorded in summer. The room temperature varied from 22° to 27° C. The temperature dependence of the tuning fork is -0.038 ppm/°C^2 according to the data sheet.

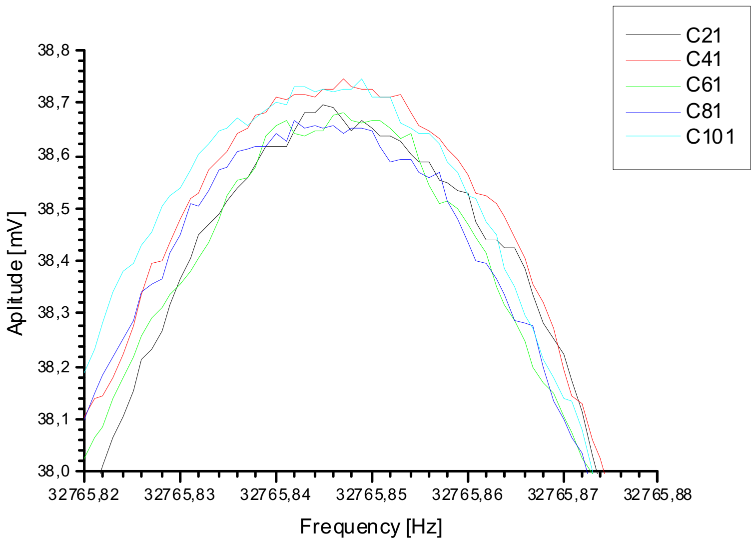

Figure 9. Stability of the frequency over a 12 hour period, the interval between the presented measurement curves is 2.5 h

There is a large variety of 32768 Hz tuning forks from the same 8 mm length 3 mm diameter package cylinder. But the physical dimensions of the tuning fork vary from manufacturer to manufacturer and for the different product lines. The spring constant is connected to the physical dimensions like formula 5. The spring constant of used tuning forks varies from 1200 N/m to 42 kN/m. According to formula 1 the frequency shift is inversely proportional to the spring constant. The frequency is fixed and also the detectable frequency shift is fixed, in our case it is about 1 mHz. So it is desirable for Casimir force measurements to use tuning forks with a low spring constant, practically 3000 to 1000 N/m.

For the Casimir measurements a metallic or metallized surface is approached to the side of the tuning fork as seen in figure 4.

3.1. Sample preparation and evaporation

Great care has to be taken so that the surface roughness is less than 30 nm. The surfaces have to be clean and are then coated with gold by vacuum deposition with empirically optimized parameters. The gold is evaporated on a tungsten wire in vacuum. The quality of the surfaces is controlled with the AFM.

4. Conclusions and status of the sensor

Silicon cantilevers and quartz tuning forks are both promising for measuring the Casimir force. The silicon cantilevers are more suited for absolute force measurements, while the tuning forks show very good sensitivity and are promising for detecting changes in the Casimir force. Great care has to be taken to measure the Casimir force with both systems. Careful and precise sensor preparation, smooth and clean surfaces and careful alignment of surfaces are necessary to keep the sensitivity up.

An important conclusion is that in both cases very low k is desired in order to measure Casimir forces. In case of the tuning fork thin and small specimens are selected, because they have a low k of 1000 to 3000 N/m.

The aim of a simple and compact design was met. However it is difficult to place the sensor in an arbitrary geometry. The distance between the active surfaces has to be kept constant. For the future it is desirable to measure the distance between the two Casimir surfaces directly.

The setup is currently being improved by a plasma surface cleaning option.

Distance measurement with capacitive distance measurement or with the use of interferometry to measure the precise distance between the active Casimir surfaces is planned.

5. Outlook and usability of vacuum fluctuations for energy technologies

It was asserted by the Nobel laureate in physics, T. D. Lee, in 1981 that the vacuum could be engineered and its energy could be used [21]. Milonni devotes a whole chapter in [1] to this topic. Harold Puthoff proved in [22] that in principle energy and heat can be extracted from the vacuum. A full monograph on theoretical and practical approaches to use zero point energy was presented by T. Valone in 2007 [23]. One of the most remarkable proposals for a cyclic engine is the work of F. Pinto [24]. Pinto introduced the idea of varying effective distance or cavity size by light-induced conductivity changes in semiconductors. With this change in conductivity the Casimir force can be modulated and an engine cycle can be designed. Another approach is to reverse the Casimir force from attraction to repulsion by using surfaces with small cavities. These cavities can change the direction of the Casimir force [25].

One reason for difficulties in extracting large amounts of energy via the Casimir effect from the vacuum is the fact that real metals become nearly transparent for wavelengths below 100 nm. Real metals are only effective mirrors down to 100 nm wavelength [26]. The shorter wavelength and the higher frequencies give the highest contributions. Since real metals become nearly transparent for UV, x-ray and shorter wavelengths, these radiation parts do not contribute to the Casimir force between real metals. Looking into table 1 shows that it will be very difficult to extract usable amounts of energy using the Casimir effect between real metals. Lambrecht et al. give a comprehensive calculation and estimation of the correction factor in real metals due to the frequency dependency of the absorption and the influence of the temperature [26].

Table 1. Casimir energy for different effective areas and separation distances

Casimir Energy	Smallest Separation d			
Effective Area A	100 nm	1 nm	1 pm	1 fm
1μm^2	4.33 10^{-13} J	4.33 10^{-7} J	433 J	4.33 10^{11} J
1 m^2	4.33 10^{-7} J	0.433 J	4.33 10^{8} J	4.33 10^{17} J
100 m^2	4.33 10^{-3} J	4.33 10^{3} J	4.33 10^{12} J	4.33 10^{21} J
1 km^2	0.433 J	4.33 10^{5} J	4.33 10^{14} J	4.33 10^{23} J

One can clearly see from table 1 that usable energy amounts are achievable with sub-atomic separation distances. Electron plasma waves or other formations of electrons could provide such conditions of small effective distances [27].

Another promising approach is to change the energy density of the zero-point energy by means of geometry. In this case the surface consists of micro cavities. This gives rise to a difference in the energy density. The gradient in energy density gives rise to the Casimir forces. This could lead to interesting engine cycles. If the cycle has a positive energy yield and a high repletion rate, then large amounts of energy can be extracted via this means [25].

It seems necessary to use more innovative and creative approaches than to simply squeeze metal surfaces as discussed in "Gedanken spacecraft …" by Forward [28].

Finally looking at the lower right sector of table 1 it is clear that large amounts of energy can be converted, if the effective distances are small enough (< nm) and the effective areas are large enough (> 1m^2). Effective setups have to be beyond gross physical macroscopic structures. Even nano-technology dimensions are too large for this type of energy extraction. Nuclear distances or electron size distances would be much more effective and would yield enough energy to power machines and spacecrafts, but seam far away from reach today.

Another possible way to enhance the difference in quantum vacuum energy in different regions is to reduce or enhance the probability of these vacuum fluctuations. Brenda Dunne, Robert Jahn and others [29] have shown that random processes can be influenced by human intention. After 25 years of research and thousands of runs with hundreds of individuals their experiments show that the influence is in the range of 0.1% [30]. If by this method random processes in the vacuum fluctuations could be changed, even by a small fraction of the 0.1 %, the extracted energy would be orders of magnitude larger than by Casimir cavities. As an outlook, we propose that experimenters and inventors trying to tap vacuum fluctuation energy should take into consideration that the human intention could make a significant difference. The influence of the human intention on vacuum fluctuations has to be studied experimentally in order to come to scientifically valid conclusions. The author aims for such experiments. At this point this is a scientifically based possibility, but too little is known on the physics of human intention to predict physical consequences.

Therefore the continuation of this type of experiments seems promising in order to obtain insights into a novel mechanism for energy conversion.

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References

[1] Milonni P. 1994 *The Quantum Vacuum.* San Diego, CA: Academic

[2] Parsegian V A. 2006 *Van der Waals Forces.* New York, NY Cambridge University

[3] Bordag M (ed). 1999 *The Casimir Effect 50 Years Later.* Singapore: World Scientific

[4] Lamoreaux S K. 1997 *Phys. Rev. Lett.* **78** 5-8.

[5] Mohideen U and Roy A. 1998 *Phys Rev Lett* **81** 4549-52.

[6] Onofrio R. 2006 *New J. Phys.* **8** 237.

[7] Klimachitskaya G L, Mohideen U, Mostepanenko V M. 2009 *Rev Mod Phys* **81** 1827.

[8] Rähmer B, Pristovsek M, Breusing M, Kremzow R and Richter W. 2006 *Appl. Phys. Lett.* **89** 063108.

[9] Karrai K and Tiemann I. 2000 *Phys. Rev. B* **62** 13174.

[10] Seo Y, Cadden-Zimansky P and Chandrasekhar V. 2005 *Appl. Phys. Lett*. **87** 103103.

[11] Rubio-Bollinger G, Joyez P and Agrait N. 2004 *Phys. Rev. Lett.* **93** 116803.

[12] Stuart-Watson D and Tapson J. 2004 *Rew. Sci. Instr.* **75** 3045.

[13] Grober R D, Acimovic J, Schuck J, Hessman D, Kindlemann P J, Hespanha J, Morse A S, Karrai K, Tiemann I and Manus S. 2000 *Rev. Sci. Instr.* **71** 2776.

[14] Karrai K 2000 *Lecture Notes on Shear and Friction Force Detection with Quartz Tuning Forks.* Proc. "Ecole Thématique de CNRS" on near-field optics, La Londe les Maures, France. (Preprint www.nano.physik.uni-muenchen.de/publikationen/Preprints/index.html p-00-03)

[15] Karrai K and Grober R D. 1995 *Appl. Phys. Lett.* **66**, 1842.

[16] Giessibl F J. 2000 *Appl. Phys. Lett.* **76**, 1470.

[17] Rensen W H J, Ruiter A G T, West P E and Van Hulst N F. 1999 *Appl. Phys. Lett.* **75** 1640.

[18] Callaghan F D, Yu X and Mellor C J. 2002 *Appl Phys. Lett.* **81** 916.

[19] Qin Y and Reifenberger R. 2007 *Rev. Sci. Instr.* **78** 063704.

[20] Ludwig T. *J. Phys. A* 2008 Math. Theor. **41** 164025.

[21] Lee T D. 1981; Particle Physics and introduction to field theory, Harwood, New York.

[22] Puthoff. 1993 *Phys. Rev. E* **48**, 1562.

[23] Valone T. 2007; *Zero Point Energy*, Integrity Research Institute.

[24] Pinto F. 1999 *Phys rev B* **60** 14740

[25] Maclay J. 2000 *Phys. Rev. A* **61**, 052110

[26] Lambrecht A. 2000 *Phys. Rev. A* **62**, 012110

[27] King M. *Tapping Zero Point Energy*. Paraclete Publishing: Provo UT; 1989.

[28] Maclay J, Forward R L. *Foundations of Physic* 2004;**34**:477

[29] Jahn R G, Dunne B J. *Consciousness and the Source of Reality*. ICRL Press; 2011 Princeton, New Jersey

[30] Jahn R G, Dunne B J. *The Pear Proposition*. Journal of Scientific Exploration; 2005, Vol. 19, No. 2, pp. 195–245.