The Aladin2 experiment: status and perspectives

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Abstract. Aladin2 is an experiment devoted to the first measurement of variations of Casimir energy in a rigid cavity. The main scientific motivation relies on the possibility of the first demonstration of a phase transition influenced by vacuum fluctuations. The principle of the measurement, based on the behaviour of the critical field for an in-cavity superconducting film, will be only briefly recalled, being discussed in detail in a different paper of the same conference (G. Bimonte et al.). In this paper, after an introduction to the long term motivations, the experimental apparatus and the results of the first measurement of sensitivity will be presented in detail, particularly in comparison with the expected signal. Last, the most important steps towards the final measurement will be discussed.

1. Introduction

The last decade has seen impressive improvements in the measurements of Casimir force [1] and this has triggered renewed interest in more general direct measurements of vacuum fluctuation effects. In a recent paper [2], pointing out the lack of any experimental verification of the vacuum energy gravitational interaction, we noticed that the present macroscopic small force detectors, like the gravitational wave interferometers, might have the sensitivity to measure the extremely small forces exerted by the earth gravitational field on a suitable Casimir cavity. As we pointed out, the possibility of success is linked both to the realization of a many-cavities layered rigid structure and to an efficient modulation of the Casimir energy. As an example, for a 10⁶-cavities structure consisting of alternate layers of aluminum (100 nm) and alumina (5 nm), with 0.5 modulation depth and tens Hz modulation frequency, the signal might be detected in one month integration time with a signal-to-noise ratio of about 100. The peculiar properties of such cavities, jointly with modulation depths, make the measurement virtually impossible at this moment of time; nevertheless, the compatibility of such experimental conditions with a not too optimistic progress in film

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depositions has “triggered” us in searching for methods for the modulation of Casimir
energy in a rigid cavity without, of course, exchanging with the system an energy too
bigger than the modulated Casimir energy itself, to avoid destroying any possibility
of measurement and control. In this spirit we have analyzed the possibility to induce
variations of energy by realizing the cavity mirrors with materials that can undergo
superconducting transitions. A variation of Casimir energy is expected because the
mirrors’ reflectivity changes, while other exchanged energy is expected to be small,
being linked to the condensation energy. The use of a phase transition offers not
only the possibility to perform the energy variation, but also an interesting method
to measure it. If the condensation energy and the variation of Casimir energy are
of comparable magnitude it can be expected that the latter may have a measurable
effect on the transition itself. This is indeed the case if the transition is obtained by
means of an external applied magnetic field. For a given temperature, the external
field needed to destroy superconductivity, i.e. the critical field, is in fact proportional
to the total variation in free energy between the normal and superconducting state
at zero field: if the condensation energy and Casimir variation are comparable, the
total energy variation, and thus the critical field, of a film being part of a cavity can
be sensibly different from that of a simple film. The Aladin2 experiment has been
conceived to verify this hypothesis, demonstrating the effect of vacuum fluctuations
on a phase transition; the study of the possibility to modulate Casimir energy to
verify its gravitational interaction, which was the original starting point, remains as
a long term motivation. The project has been funded by the Italian INFN (Istituto
Nazionale di Fisica Nucleare) and recently has been joined by the German IPHT
(Institut Für Physikalische HochTechnologie). The final measurement is foreseen for
the end of 2007. Although the ideal cavity would be a five-layer structure [5, 3], the
actual cavity is a three-layer structure that warrants a safer realization and electrical
contacting: a thin film of superconducting metal, a dielectric layer and a final film of
normal metal. The cavity is placed at cryogenic temperature and an external magnetic
field is applied, parallel to the plane of the films. The applied field necessary to destroy
superconductivity \( H_{\parallel}^{C}(T) \) is measured as a function of temperature. The expected signal
is a different behaviour of the function \( H_{\parallel}^{C}(T) \) with respect to the critical field \( H_{\parallel}^{F}(T) \)
of simple film. Details on calculations and on other theoretical aspects can be found in
a proceedings paper of this same conference [3]. In the present paper, after recalling the
expected signal for the actual experimental configurations, we will report on our present
sensitivity and next experimental steps.

2. Expected signal and sensitivity limits

As shown in detail in [3], a good choice for the cavity configuration is a structure having
a first superconducting film of 5 nm thickness, a second dielectric layer 10 nm thick
and a final metal layer 100 nm thick. The shift in magnetic field is maximized for low
condensation energies, so that superconductors having a low \( T_c \) should be preferable.
Nevertheless, measurements at very low temperatures could be particularly difficult and time consuming, not easily allowing a high number of measurements and statistical analysis. As a good compromise between amplitude of expected signal and multiple measurements we choose to work in the 1 K region of temperatures, where the cooling down time is relatively short and the measurements can be performed on typically well known soft superconductors (like Aluminum, Zinc, Tin or even Beryllium if deposited on cooled substrate [7]). To illustrate the expected signal, in fig. 1 $H_{\parallel}(T)$ is reported for a single film (dashed curve) and for an in-cavity film (green and black curves) in the optimal configuration of first and third layers made of Beryllium and the intermediate layer of a native oxide.

As is seen in the figure the in-cavity film, for reduced temperature $t = \frac{T}{T_c}$ approaching unity (not valid in a neighbourhood [4]), should exhibit an $H^C(t)$ which deviates from the usual law $H^F(t) \propto \sqrt{1-t}$ valid for single film. The ratio of the field shift and simple film field $r = \frac{H^F(t) - H^C(t)}{H^F(t)}$ is five-tens percent for reduced temperature sufficiently far from $T_c$, so that the signal should be quite easily measurable. Unfortunately, although Beryllium is a very promising material, its toxicity makes it difficult to find it in the market (at least properly deposited) and also to be home deposited. For this reason we have decided to start the experimental work with more handily materials like Aluminum and Zinc. In particular, Aluminum has been chosen since it is a very well known material and can be used to test the sensitivity of the experimental apparatus, while Zinc is expected to have a sufficiently low condensation energy to exhibit a measurable signal. Calculations show that the nature of the intermediate oxide layer does not affect sensibly the field shift, while metallic properties of the third layer, in particular plasma frequency and mean free path, heavily do [3, 4].

The situation is described in fig. 2, where the ratio $r$ is reported for various configurations: first layer of Aluminum and third layer of Gold (red curve), Zinc and Gold (black curve), Zinc and “perfect reflector mirror” (blue curve).

The work of our group is also devoted, at present, to discovering which materials have a sufficiently high plasma frequency and mean free path to approach the behaviour...
of a perfect mirror. Among the metals Beryllium is the best but, again in light of its toxicity, further analysis is devoted to finding whether some alloy or compound might be used instead. From fig. 2 it can be seen that, in case of Zinc with not optimal mirror reflectivity (Gold), the sensitivity $\delta r$ in the measurement of critical field must be of order $\delta r = \frac{\Delta H}{H} \approx 5 - 10/1000$ in the temperature range of interest, and the sensitivity on measurement of the reduced temperature $\delta t$ of order $\delta t \leq \delta r(\frac{1}{H} \frac{\partial H}{\partial t})^{-1} \approx 3 \times 10^{-4}$, corresponding to the sensitivity in absolute temperature $\delta T \approx 0.25$ mK. It is important to point out that, in this experiment, alignment requirements are quite stringent: from the formula $\frac{\delta H}{H} = \frac{1}{H} \frac{\partial H}{\partial \theta} \delta \theta = \frac{H}{H} \delta \theta$, where $\theta$ is the angle between field and sample plane, the penetration depth $\lambda$ is typically of order 50-100 nm. On considering a film thickness of 5 nm we obtain, near transition, $\frac{H}{H} \approx \sqrt{24 \lambda D} \frac{1}{\sqrt{1 - t}}$ which imposes the stringent limit $\delta \theta < 3 \times 10^{-5}$ rad (Zinc/Gold), relaxed to $\delta \theta < 10^{-4}$ rad for Zinc and perfect mirror.

3. Apparatus description and sensitivity tests

The cryogenic apparatus consists of the commercial cryostat Oxford Instruments HELVLTD HelioxVL 3He inserted in a HD120H transport dewar, reaching the base temperature of 300 mK. The external field is generated by a 1.1 Gauss/mAmpere superconducting coil and the current is supplied and measured with a sensitivity better than 1/1000 by a multimeter HP 34401A. The sample can be oriented parallel (and orthogonal) to the magnetic field, aligned by construction with an estimated accuracy of about $10^{-2}$ rad. Possible alignment improvements will be discussed in the next section. The measurement method is a standard omodine four-wire resistance. To test the sensitivity of cryogenic apparatus a film of 300 nm thickness has been used, so as to have far less stringent limitations on misalignments. The lock-in frequency is 6 Hz and probe current of 10$\mu$A. The resistance of the film before transition is $R = 24m\Omega$. The actual measurement is performed by fixing the external field and storing $R(T)$. A set
of measurements is reported in fig. 3: the transition width is approximately 10 mK, the measured residual resistance is about 1 mΩ. The sensitivity of the measurement $\delta R \approx 1m\Omega$ is limited by the noise current at first stage of the read-out electronic. The present limit is thought to be sufficient also for the final measurement, where thinner films will have about two orders of magnitude higher resistances.

The experimental data, reported in fig. 4 in the temperature region of interest, show the expected behaviour $H_{||}(t) \propto \sqrt{1-t}$. In order to estimate sensitivity in $\frac{\delta H_{||}}{H_{||}}$ the data have been fitted by taking into account that the correction resulting from nucleation is not negligible, by virtue of sample thickness. Thus, the data have been fitted with

$$H_{||}(t) = \sqrt{24H_T(0)} \frac{\lambda_c(0)}{D} \sqrt{\frac{1-t^2}{1+t^2}} \left[ 1 + \frac{9}{\pi^6} \frac{D^2}{\xi(0)^2} (1-t) \right],$$

which is valid near $T_c$, where the conditions $D < \sqrt{3} \lambda_c(t)$ and $\frac{9}{\pi^6} \frac{D^2}{\xi(0)^2}$ are satisfied. In the equation $H_T(0)$, $\lambda_c(0)$ and $\xi(0)$ are the thermodynamical field, the effective penetration depth and the coherence length at zero temperature, respectively [6].

The results of the fit are shown in fig. 4, where the experimental residuals are reported. In the same figure the red curves are the confidence bands, the green curve is the expected signal for an Aluminum/Gold cavity, the purple for a Zinc/Gold cavity and finally the blue is the Zinc expected signal if the contribution of the zero-frequency Transverse Electric mode is set to zero in the normal state.

The residuals show a sensitivity $\frac{\delta H_{||}}{H_{||}} \approx 3 \times 10^{-3}$ in the region of interest, so that $\delta t$ can be estimated as $\delta t \approx 1.5 \times 10^{-4}$, corresponding to $\delta T \approx 0.2$ mK. Last, from the fit we obtain the values $T_c = 1.2932$ K, $\sigma_{T_c} = 0.0002$ K; $\lambda_c = 104.3$ nm, $\sigma_{\lambda_c} = 0.3$ nm; $\xi(0) = 60$ nm, $\sigma_{\xi(0)} = 20$ nm K which are in the range of values compatible with the literature.
Figure 4. Critical field as a function of $\sqrt{1-t}$

Figure 5. Fit Residuals

From this measurement we find that the sensitivity of the measurement might not be sufficient to detect the Aluminum/Gold cavity signal; on the contrary, it should be sufficient to detect it in Zinc/Gold cavities, allowing also to discriminate the questioned contribution of zero frequency TE mode to Casimir energy [8] [4].

4. Next sensitivity test and experiment schedule

Although these preliminary results on cryogenic apparatus are encouraging, various improvements should be performed before we can state that the needed sensitivity has been reached. In particular, two very important effects might spoil the present sensitivity: the broadening of transition width and rising of alignment effects when passing to thinner films. In this spirit, while first experimental studies on Zinc deposition
Figure 6. Scheme of the sample: statistics will be performed on different samples

and cavity realization are carried out, a first experimental test with aluminum cavities will be performed in a short time (fall of 2005). The thickness of Aluminum layer will be 10 nm, while the third layer will be Gold (100 nm) for some cavities and Silver (100 nm) for others. Gold is chosen for its extreme simplicity in deposition, while Silver, more reflective, will be tested as a candidate for final configuration material.

As discussed previously, the requirements on alignment are quite stringent. A solution that we will test in the next run is the use, on the same sample, of two simple films, two cavities and a bridge configuration, as shown in fig. 6.

It is important to stress that our experiment looks for a different behaviour of $H_{||}(T)$ for films being or not being part of a cavity. Thus, this configuration is not aimed at improving accuracy on the measurement but rather at obtaining “on line” the different behaviour of the two cases which will have the same misalignment by construction. In this respect, we point out that we do not expect that the bridge will be compensated during the transition; it should instead exhibit a pick by virtue of imperfect equalities of the four samples: the evolution of the pick for different external applied field will be the desired evidence of the different behaviour of the film/cavity $R(T)$.

These structures are presently under construction at the IPHT (Jena) and the first measurements are foreseen by the end of the year 2005.

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