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The Aladin2 experiment: status and perspectives

Giuseppe Bimonte[1], Detlef Born[1], Enrico Calloni[1,3], Giampiero Esposito[1], Evgeni Il'ichev[2], Luigi Rosa[1], Ornella Scaldaferri[1], Francesco Tafuri[1], Ruggero Vaglio[1] and Uve Hübner[2]

[1] INFN, Sezione di Napoli and Dipartimento di Scienze Fisiche, Complesso Universitario di Monte S Angelo, Via Cintia, Edificio N', 80126 Napoli, Italy

[2] Institut Für Physikalische HochTechnologie e. V., Postfach 10 02 39-07702 Jena, Germany

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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* 2006 *J. Phys. A: Math. Gen.* **39** 6161). 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.

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(Some figures in this article are in colour only in the electronic version)

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's gravitational field on a suitable Casimir cavity. As we pointed out, the possibility of success is linked to both the realization of a many-cavities layered rigid structure and to an efficient modulation of the Casimir energy. As an example, for a 10^6-cavities structure consisting of alternate layers of aluminium (100 nm) and alumina (5 nm), with 0.5 modulation depth and tens of hertz of modulation

[3] Talk given by this author.

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 present; nevertheless, the compatibility of such experimental conditions with a not too optimistic progress in film 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 much bigger than the modulated Casimir energy itself, to avoid destroying any possibility of measurement and control. In this spirit, we have analysed the possibility of inducing 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 of performing 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 of modulating Casimir energy to verify its gravitational interaction, which was the original starting point, remains 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 at 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 a simple film. Details of calculations and of 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 the 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 the 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 aluminium, zinc, tin or

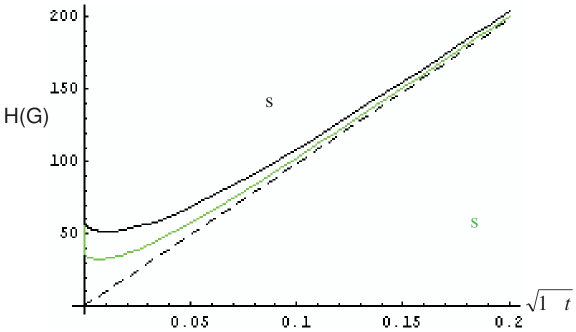

Figure 1. Critical field of beryllium; simple and in-cavity film.

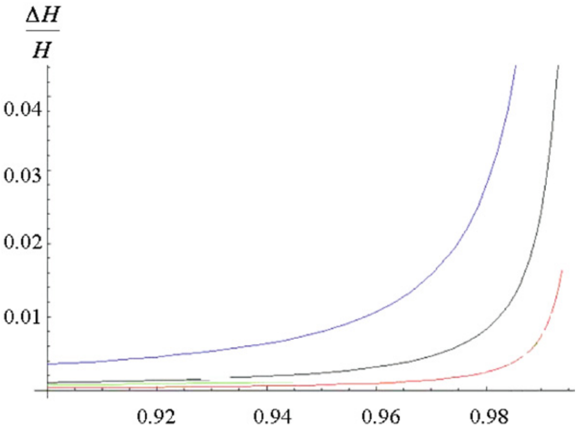

Figure 2. Expected relative field deviation.

even beryllium if deposited on a cooled substrate [7]). To illustrate the expected signal, in figure 1 $H_{\|}(T)$ is reported for a single film (dashed curve) and for an in-cavity film (upper and middle curves) in the optimal configuration of first and third layers made of beryllium and the intermediate layer of a native oxide.

As 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 a single film. The ratio of the field shift and simple film field $r = \frac{H^F(t)-H^C(t)}{H^C(t)}$ is 5–10% at 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 easily procurable materials like aluminium and zinc. In particular, aluminium 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, have a strong effect [3, 4].

The situation is described in figure 2, where the ratio r is reported for various configurations: the first layer of aluminium and the third layer of gold (lower curve), zinc and gold (middle curve), zinc and 'perfect reflector mirror' (upper curve).

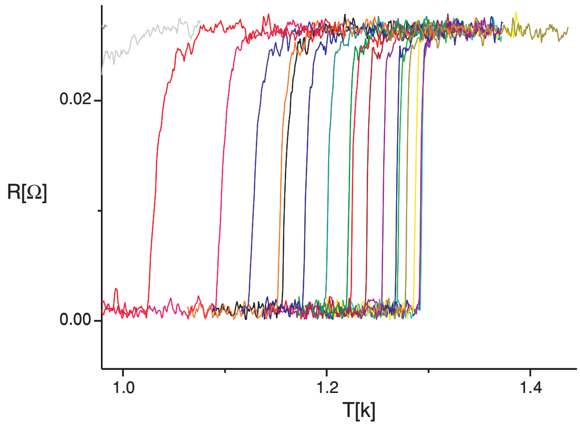

Figure 3. $R(T)$ for different applied fields on a 300 nm aluminium sample.

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 figure 2 it can be seen that, in the case of zinc with non optimal mirror reflectivity (gold), the sensitivity δr in the measurement of the critical field must be of order $\delta r = \frac{\Delta H_\parallel}{H_\parallel} \approx 5 - 10/1000$ in the temperature range of interest, and the sensitivity on measurement of the reduced temperature δt of order $\delta t \leqslant \delta r \left(\frac{1}{H_\parallel}\frac{\partial H_\parallel}{\partial t}\right)^{-1} \approx 3\times 10^{-4}$, corresponding to the sensitivity at 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 [6] $\frac{\delta H_\parallel}{H_\parallel} = \frac{1}{H_\parallel}\frac{\partial H_\parallel}{\partial \theta}\delta\theta = \frac{H_\parallel}{H_\perp}\delta\theta$, where θ is the angle between the field and sample plane, the penetration depth λ is typically of order 50–100 nm. On considering a film thickness of 5 nm we obtain, near transition, $\frac{H_\parallel}{H_\perp} \approx \sqrt{24}\frac{\lambda}{D}\frac{1}{\sqrt{1-t}}$ 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 an HD120H transport dewar, reaching the base temperature of 300 mK. The external field is generated by a 1.1 G mA^{-1} 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 coherent detection 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 10μA. The resistance of the film before transition is $R = 24$ mΩ. The actual measurement is performed by fixing the external field and storing $R(T)$. A set of measurements is reported in figure 3: the transition width is approximately 10 mK, the measured residual resistance is about 1 mΩ. The sensitivity of the measurement $\delta R \approx 1$ mΩ is limited by the noise current at

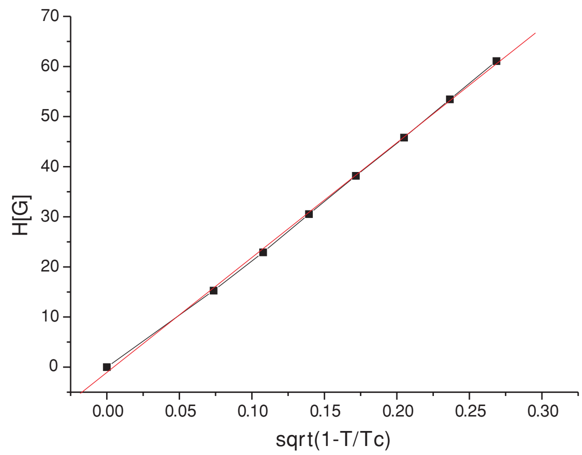

Figure 4. Critical field as a function of $\sqrt{1-t}$.

the first stage of the read-out electronics. 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 figure 4 in the temperature region of interest, show the expected behaviour $H_{\parallel}(t) \propto \sqrt{1-t}$. In order to estimate sensitivity in $\frac{\delta H_{\parallel}}{H_{\parallel}}$ 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

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

which is valid near T_c, where the conditions $D < \sqrt{5}\lambda_e(t)$ and $\frac{9}{\pi^6}\frac{D^2}{\overline{\xi}(0)^2}$ are satisfied. In the equation, $H_T(0)$, $\lambda_e(0)$ and $\overline{\xi}(0)$ 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 figure 5, where the experimental residuals are reported. In the same figure the lower (and the symmetric) curves are the confidence band, the curve inside the confidence band is the expected signal for an aluminium/gold cavity, the upper curve for a beryllium/beryllium cavity, the middle curves refer to a zinc/gold cavity if the contribution of the zero-frequency transverse electric (TE) mode is set to zero (middle-upper) or not (middle-lower) in the normal state.

The residuals show a sensitivity $\frac{\delta H_{\parallel}}{H_{\parallel}} \approx 3 \times 10^{-3}$ in the region of interest, so that δt 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; $\lambda_e = 104.3$ nm, $\sigma_{\lambda_e} = 0.3$ nm; $\overline{\xi}(0) = 60$ nm, $\sigma_{\overline{\xi}(0)} = 20$ nm K, which are in the range of values compatible with that in the literature.

From this measurement, we find that the sensitivity of the measurement might not be sufficient to detect the aluminium/gold cavity signal; in contrast, it should be sufficient to detect it in zinc/gold cavities, allowing us to also 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

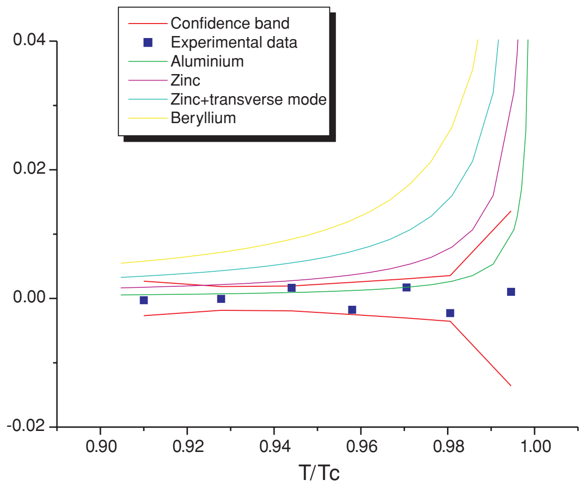

Figure 5. Fit residuals.

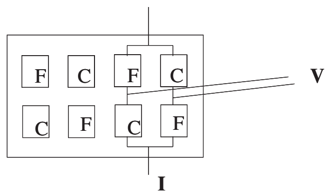

Figure 6. Scheme of the sample: statistics will be performed on different samples.

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 and cavity realization are carried out, a first set of experimental tests on aluminium cavities will be performed in the next few months. The thickness of aluminium 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 figure 6.

It is important to stress that our experiment looks for a different behaviour of $H_{\parallel}(T)$ for films being or not being part of a cavity. Thus, this configuration is not aimed at improving accuracy of the measurement but rather at obtaining by hardware a direct signal of the expected 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 fields 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 complete set of measurements is foreseen for summer 2006.

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