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Archimedes: The weight of quantum vacuum

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Summary. — The Archimedes experiment investigates whether the zero-point energy of the electromagnetic field interacts with gravity, addressing one of the most long-standing discussions in modern physics, the Cosmological Constant Problem. By using a highly sensitive beam balance, the experiment aims to detect weight variations resulting from the modulation of vacuum energy in a Casimir cavity, as the plates forming the cavity become reflective while undergoing a superconducting transition. If interaction occurs, an upward force resembling Archimedes' buoyancy effect is expected. The experiment prototype, located in the low-noise SarGrav Laboratories in Sardinia, has achieved a torque sensitivity of about 7×10^{-13} Nm/$\sqrt{\text{Hz}}$ at tens of mHz, which is compatible with the thermal noise estimation, validating both the optical and mechanical design of the system.

1. – Introduction

Archimedes is a fundamental physics experiment intending to measure the interaction between quantum vacuum fluctuations and the gravitational field. While quantum electrodynamics in flat spacetime is a well-established theoretical framework, its coupling with gravity remains a topic of ongoing debate and investigation. One of the significant challenges in this context is the Cosmological Constant Problem [1]. Quantum field theory predicts a very large energy density for the vacuum, and this density should have large gravitational effects. However, these effects have never been observed, and the discrepancy between theory and observation is of 120 orders of magnitude, which is why it has been addressed to as "the worst theoretical prediction in the history of physics."

The Archimedes experiment seeks to address this challenge by directly measuring the gravitational coupling of vacuum energy, testing whether virtual quanta follow geodesics. When a rigid Casimir cavity is suspended, the vacuum fluctuations should contribute an additional negative weight, given by

$$\vec{P} = \frac{E_C}{c^2}\vec{g}, \tag{1}$$

where c is the speed of light, $\vec{g}$ is the gravitational acceleration, and in the ideal case of perfectly reflecting plates, $E_C = -\pi^2\hbar c/720a^3$ represents the Casimir Energy, where a is the distance between the plates of the cavity [2]. The experiment is composed by a highly sensitive cryogenic beam balance to measure the weight of vacuum energy confined within a sample composed of stacked Casimir cavities.

Currently, the experiment, with its prototype, is installed in the SarGrav Laboratory, located in the seismically quiet Sos Enattos former mine near Lula, Sardinia, Italy. This site is also a proposed candidate for the Einstein Telescope, the next-generation European gravitational wave detector [3].

The following sections provide an overview of the experiment: sect. **2** introduces the working principle and the expected signal; in sect. **3**, the mechanical setup is described, including the optical readout and control systems; sect. **4** focuses on the superconducting samples and the signal modulation technique they undergo; finally, sect. **5** analyzes the sensitivity of the instrument.

2. – Working principle and expected effect

To investigate the interaction between quantum vacuum fluctuations and gravity, we use massive samples suspended from a precision balance. These samples are specifically chosen to store vacuum energy exploiting the Casimir effect. The Casimir effect is a quantum phenomenon that arises when two uncharged conductive plates are placed nanometers apart in a vacuum. This effect results from the interference of zero-point electromagnetic modes [4]. In free space, electromagnetic fluctuations occur at all wavelengths, but the plates suppress modes with wavelengths exceeding twice the cavity spacing. This limitation reduces the vacuum energy density inside the cavity, resulting in a lower total zero-point energy compared to the outside. As a consequence, a small but finite inward force is generated between the plates, inversely proportional to the fourth power of their separation.

If such a rigid Casimir cavity is placed in a gravitational field and the vacuum possesses weight, the gravitational field would exert an upward force on the cavity, analogous to Archimedes' principle in fluids. This force would correspond to the weight of the suppressed modes within the cavity and would act in the opposite direction of gravitational acceleration. For a single cavity with an area of $1\,\mathrm{dm}^2$ and a distance between the plates of $1\,\mu$m, the expected force is approximately $4 \times 10^{-28}\,\mathrm{N}$ [2].

However, considering a single cavity to measure this force would be impractical. To obtain a measurable force we consider a stratified superconductive sample, that is equivalent to a stack of a large number of Casimir cavity, each with separation of planes of the order of few nanometers. The force cannot be detected in DC and must instead be modulated, which we accomplish by modulating the system's temperature.

In this setup, high-temperature superconductors (HTS) are used as a stack of Casimir cavities. Cuprates, a class of HTS, are formed by parallel layers of copper oxide (CuO) separated by insulating intermediate layers. Above their critical temperature, cuprates are poor conductors, but below this temperature, the CuO planes become superconducting while the intermediate layers remain insulating [5]. The Casimir energy between these planes contributes to the superconducting condensation energy [2, 6, 7] and, at a macroscopic level, can be modeled as plasma sheets separated by vacuum [8].

Small weight variations are induced by thermally modulating the superconducting transition in the sample. This modulation is performed slowly to avoid introducing extraneous energy into the system.

3. – Mechanics and control of the Archimedes balance system

The Archimedes experimental setup is a very high-sensitivity beam balance designed for precise torque measurements. As shown in the sketch in fig. 1(a), the balance is composed of two arms: the *Measurement Arm* and the *Reference Arm*.

The Measurement Arm is a hollow, square-section rod (20×20 mm), with a length of 1.26 m and mass of 1.1 kg. To ensure a quick response to tilt, the arm is designed with a low moment of inertia. The Measurement Arm is suspended by two double-ended Cu-Be flexible joints, each with a cross-sectional area of $100 \times 200\,\mu$m.

The Reference Arm, on the other end, is designed to reject common-mode seismic noise. It has a significantly higher moment of inertia and is much heavier than the measurement arm. It consists of a solid aluminum rod 42 cm in length and 5×5 cm in cross-section. The ends of the Reference Arm are weighted with two solid tungsten dumbbells, each weighing 4.25 kg, for a total weight of 10 kg. Like the Measurement Arm, the Reference Arm is suspended by Cu-Be flexible joints, but these are thicker (3×0.1 mm) to support the greater weight of the arm.

The angular displacement of the arms is measured using two distinct readout systems: a coarse measurement of angular displacement is provided by an Optical Lever. It consists of a light source, a superluminescent diode (sLED), directed via a beam splitter onto a mirror mounted on the arm. The reflected light strikes a Position Sensitive Detector (PSD), which is a 2×2 quadrant detector fixed to the ground. The analog signals from the four quadrants (top-left, top-right, bottom-left, bottom-right) are processed to calculate vertical and horizontal asymmetries, as well as a normalized total signal

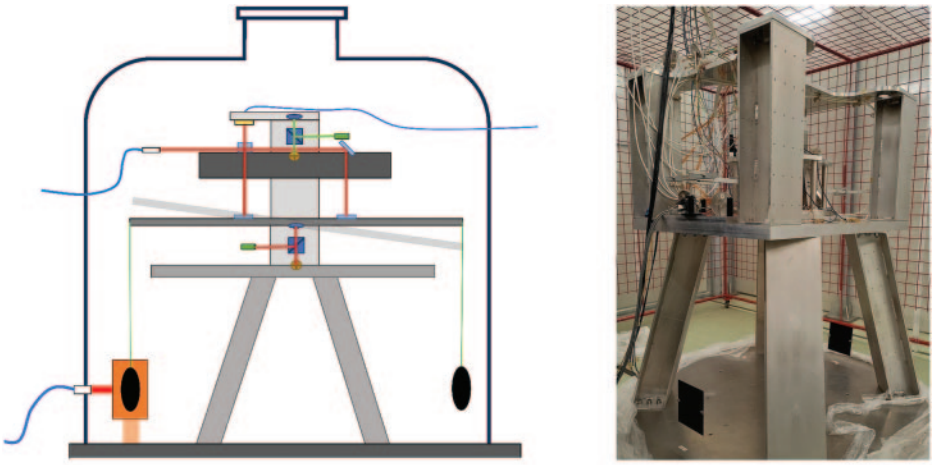

Fig. 1. – The experimental balance operates under controlled conditions with a vacuum pressure of $P = 10^{-6}$ mbar and a cryogenic temperature of $T = 90$ K. The laser power, used to heat the samples, is modulated as a square function, remotely driven at a chosen frequency. The temperature of the samples is modulated around their superconducting transition point using the controlled laser heating system. This thermal modulation induces a small tilt oscillation in the balance, which is directly related to the modulated weight variations of the samples. The tilt of the Measurement Arm relative to the Reference Arm is monitored using a Michelson interferometer.

that eliminates laser power fluctuations. There is also a Michelson Interferometer: this system provides finer measurements and is illuminated by a Nd:YAG Mephisto laser ($\lambda = 1064\,\mathrm{nm}$). The interferometer operates in direct current (DC) mode and measures angular displacement with high precision.

The Measurement Arm is equipped with both of readout systems, while the Reference Arm is only provided with the optical lever. A control system is employed to maintain the working position of both arms, ensuring that the Measurement Arm stays aligned with the mid-fringe of the interferometer. At the same time, the optical lever signals for the Reference Arm are kept at zero, indicating the horizontal position. Feedback control is applied to each interferometer arm using electrostatic actuators located at the ends of the arms.

Currently, data is collected, filtered, and sent to the actuators using a National Instruments C-RIO ADC/CPU/DAC system.

A picture of the actual apparatus is shown in fig. 1(b).

4. – Cryogenic samples, thermal modulation and cryostat

The experimental apparatus will operate at cryogenic temperatures and it will detect tiny forces by modulating the temperature of superconducting samples around their critical transition temperature, approximately 90 K. At each end of the Measurement Arm, a superconducting sample with a mass of 200 g is suspended. These samples are prepared with different levels of oxygen doping, ensuring that only one of them undergoes a superconducting transition when the temperature is lowered below the critical point. This transition results in the microscopic formation of stacked Casimir cavities.

High-Tc cuprate materials are used to achieve this, due to their intrinsic multi-cavity structure associated with high-temperature superconductivity. Candidate materials, such as rare-earth barium copper oxides, are evaluated based on the following criteria: a sharp superconducting transition, which is essential for maximizing the effect, closely tied to the performance characteristics of HTS materials; effective thermal exchange with the radiative bath, that must be ensured and is dependent on the sample geometry and its specific heat capacity; a mass of approximately 200 g, necessitating the production of a cylindrical sample roughly 100 mm in diameter.

For the Archimedes experiment, careful consideration is given to the selection of HTS materials. Currently, $GdBi_2C_3O_{7-x}$ is a strong candidate due to its transition temperature of 93.5 K, narrow transition width of 1 K (a measured transition is shown in fig. 2), its demonstrated feasibility for production at the required 100 mm diameter and the possibility to realize large scale samples with several shapes [9].

To enable thermal modulation, each sample is placed in a thermal bath, where blackbody radiation energy is supplied. It is crucial that the system is entirely isolated from external forces to avoid spurious effects on the samples. Irradiation is performed using a copper box with thin walls which are heated by a high-power laser. This approach eliminates the risk of introducing spurious currents, as might occur with serpentine heating. To anticipate temperature variations under these experimental conditions, finite elements simulations are being conducted and will be validated via comparison with experiments performed in a simplified cryostat. These simulation results are currently undergoing validation against experimental measurements.

The entire experimental setup is contained within a three-chamber steel cryostat. The innermost chamber is evacuated to a vacuum level of mbar, while the second chamber is filled with liquid nitrogen. Both of these chambers are enclosed within an external shield,

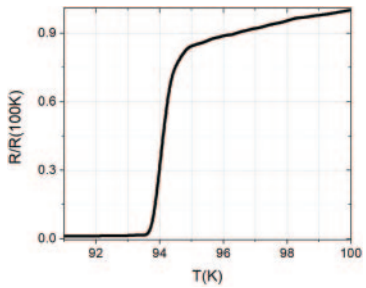

Fig. 2. – Measured superconducting transition of a GdBCO sample characterized for the experiment. A sharp transition is crucial to facilitate the thermal modulation of the force.

where a vacuum is also maintained. This three-layer shielding design offers enhanced isolation from external environmental influences.

5. – Torque sensitivity and temperature modulation

In preliminary tests without suspended samples, the balance was used as a ground tilt sensor, demonstrating remarkable sensitivity [10]. The measurement, aimed at detecting a signal associated with the vacuum weight, will be performed by modulating the temperature of the samples around their superconducting transition point. The modulation frequency is determined by two main factors: achieving thermal equilibrium during each cycle and operating within the frequency range of maximum balance sensitivity, between 5 and 100 mHz.

For a sample with a diameter of 100 mm and thickness of 5 mm, the expected signal is approximately 10^{-16} N, modulated at a frequency of about 10 mHz. With an integration time of 10^6 seconds (approximately two weeks) and a balance arm length of 1.4 m, the system is designed to achieve a spectral torque sensitivity better than $10^{-13}\frac{\mathrm{Nm}}{\sqrt{\mathrm{Hz}}}$ at the modulation frequency.

The sensitivity of the prototype (fig. 3) reaches approximately $7\times10^{-13}\frac{\mathrm{Nm}}{\sqrt{\mathrm{Hz}}}$ at 10 mHz [10], which is nearly limited by the thermal noise curve. To meet the required torque

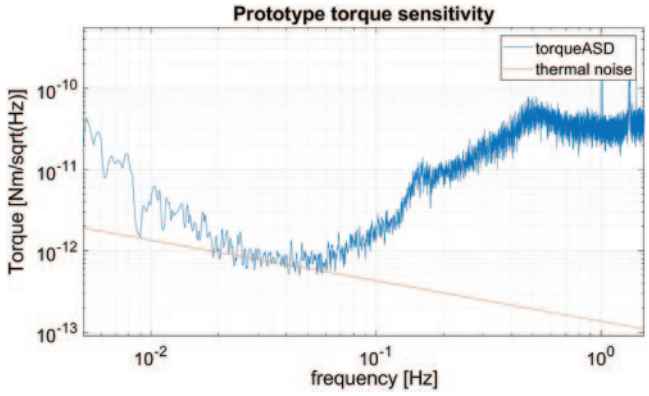

Fig. 3. – Prototype sensitivity and thermal noise [10].

sensitivity, the final balance must be able to withstand torques approximately 10 times greater than the current limit. This improvement will benefit from a cryogenic environment that reduces thermal noise and enhances quality factor of the suspension, which is currently under study.

6. – Conclusions

The question of why the zero-point energy of the vacuum does not produce a large cosmological constant remains one of the most significant unsolved problems in modern physics, known as the Cosmological Constant Problem. In this context, the Archimedes experiment was conceived to measure the gravitational coupling of vacuum fluctuations by confining them within a rigid Casimir cavity.

Initially proposed in the late 2000 s, the experiment is now fully under construction and undergoing partial testing in the seismically quiet region of Sardinia, Italy. With its measurement campaign set to begin, the Archimedes experiment holds the promise of providing new insights into one of cosmology's greatest mysteries.

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