Exploring Vacuum-Gravity Interaction through the Archimedes Experiment: Recent Results and Future Prospects

V. Mangano[1,2,*], *A.* Allocca[3,4], *S.* Avino[4,5], *A.* Cabras[1], *L.* Caggiu[1], *E.* Calloni[3,4], *S.* Caprara[6,7], *A. F. S.* Cardoso[1], *M.* Carpinelli[8,9,10], *C.* Cau[1], *A.* Contu[2], *R.* De Rosa[3,4], *L.* D'Onofrio[7], *D.* D'Urso[1,2], *S.* Enzo[1], *L.* Errico[3,4], *M.* Esposito[3,4], *G.* Gagliardi[4,5], *S.* Garroni[1], *M.* Grilli[6,7], *M.* Marsella[6,7], *G.* Mulas[1,2], *F.* Murgia[1,2], *L.* Naticchioni[7], *A.* Pasqualetti[10], *G. P.* Pepe[3,4], *M.* Perciballi[,**], *P.* Puppo[7], *P.* Rapagnani[6,7], *F.* Ricci[6,7], *L.* Rosa[3,4], *C.* Rovelli[11,12,13], *D.* Rozza[8,9], *P.* Ruggi[10], *N.* Saini[6,7], *V.* Sequino[3,4], *V.* Sipala[1,2], *D.* Stornaiuolo[3,4], *F.* Tafuri[3,4], *L.* Trozzo[4], and *M.* Tuveri[2,14]

[1]Dipartimento di Scienze Chimiche, Fisiche, Matematiche e Naturali, Università di Sassari, Via Vienna 2, 07100, Sassari, Italy
[2]Istituto Nazionale Fisica Nucleare - Sezione di Cagliari, Monserrato, 09042, Cagliari, Italy
[3]Dipartimento di Fisica, Università di Napoli Federico II, Via Cinthia, 80126, Napoli, Italy
[4]Istituto Nazionale di Fisica Nucleare - Sezione di Napoli, Via Cinthia, 80126, Napoli, Italy
[5]Consiglio Nazionale delle Ricerche - Istituto Nazionale di Ottica, SS Napoli, Via Campi Flegrei 34, 80078, Pozzuoli, Italy
[6]Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, 00185, Roma, Italy
[7]Istituto Nazionale Fisica Nucleare - Sezione di Roma, Piazzale Aldo Moro 2, 00185, Roma, Italy
[8]Dipartimento di Fisica, Università degli Studi di Milano-Bicocca, Piazza della Scienza 3, 20126, Milano, Italy
[9]Istituto Nazionale Fisica Nucleare - Sezione di Milano-Bicocca, Piazza della Scienza 3, 20126, Milano, Italy
[10]European Gravitational Observatory - EGO, Via Edoardo Amaldi, 56021, Cascina, Italy
[11]Campus of Luminy, Centre de Physique Theorique, Case 907, Marseille 13288, France
[12]Aix Marseille Université, CNRS, CPT, UMR 7332, Avenue Robert Schuman, Marseille 13288, France
[13]Université de Toulon, CNRS, CPT, UMR 7332, Avenue de L'Université, La Garde 83130, France
[14]Dipartimento di Fisica, Università degli Studi di Cagliari, Monserrato, 09042, Cagliari, Italy

Abstract. The goal of the Archimedes experiment is to investigate the role of the interaction between the vacuum fluctuations and gravitational field. This will be possible thanks to a high sensitivity and cryogenic balance installed in the SarGrav laboratory in the Sos Enattos mine (Sardinia), the Italian candidate site for the third generation gravitational wave observatory Einstein Telescope. Archimedes will measure the small weight variations induced in two high temperature superconductors that have the property of "trapping" or "expelling" vacuum energy when their temperatures are greater or lower than their critical temperatures. Only the radiative heat exchange mechanism must be used to remove or add thermal energy to the sample as it must be isolated from any external interaction that could add energy other than the vacuum one. The status of the experiment will be illustrated together with the most recent results.

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[*] e-mail: vmangano@uniss.it
[**] deceased

1 Introduction

The Archimedes project [1, 2] explores the potential interaction between quantum vacuum energy fluctuations and the gravitational field. This could provide insights into the so-called Cosmological Constant Problem [3, 4] (Quantum Mechanics predicts a vacuum energy density hugely greater - by about 120 orders of magnitude - than what is observed in Cosmology) and into the nature of dark energy (identified with vacuum energy and probable cause of the accelerated expansion of the universe).

The existence of the quantum vacuum energy fluctuations is experimentally demonstrated by the Casimir effect [5]. Archimedes focuses on observing whether these fluctuations have weight by measuring the gravitational effects on a Casimir cavity, which stores a specific amount of vacuum energy under well-defined boundary conditions of its plates. If the quantum vacuum energy weighs, the gravitational field will exert a force on the Casimir cavity at rest on Earth, equivalent to the weight of the modes expelled from the cavity [2, 6–9]. For instance, when the plates are superconducting, the vacuum energy within the Casimir cavity is better expelled: this results in a reduction of the vacuum energy inside it and a corresponding decrease of its weight [6–8].

High-temperature superconductors (HTS) are crucial to this investigation due to their layered structure, which acts as a natural Casimir cavity. For a superconducting disc with a diameter of 100.0 mm and a thickness of 5.0 mm, the expected force acting on it is $\sim 5.0 \times 10^{-16}$ N [2, 10, 11].

Archimedes will employ a cryogenic and high-precision sensitivity cryogenic balance to detect the tiny vacuum weight variations in high-temperature superconductors subjected to a controlled temperature modulation. The balance is based on Michelson interferometer and optical lever technology and is housed inside a three-shield cryostat [1, 2].

2 Thermal modulation

Two identical high-temperature superconducting discs will be suspended at the ends of the balance arm. The temperature of the superconductor must be modulated around its critical temperature to induce a variation in vacuum energy and force a superconductor to switch between the superconducting and normal states. When the temperature is above (below) the critical temperature, a superconductor can trap (expel) vacuum energy, leading to an increase (lowering) of its weight. The temperature or Casimir energy of only one disc will be modulated, generating a periodic force that causes the arm to oscillate at the modulation frequency, from 5 mHz to 10 mHz. The tilt of the arm will be detected using a Michelson interferometer [1, 2].

The temperature of the superconducting sample must be modulated around its critical temperature in a very controlled way, using only radiative heat transfer. Thermal energy is exchanged between the heating system and the sample through electromagnetic radiation without physical contact or external interactions that might introduce unwanted forces or energy to the sample. The goal is to modulate the temperature using a frequency of a few tens of mHz and a maximum amplitude of 3 K around the critical temperature, as Archimedes requires. Careful attention must be paid to the design and the construction of a thermal modulation system to meet these requirements so that the selected geometry and materials can provide accurate and reliable performance.

3 Experimental results

A new and improved modulation system [2] has been developed and built to modulate the temperature of a superconducting sample in a liquid nitrogen bath and under vacuum conditions (pressure of $\sim 10^{-5}$ mbar).

The sample is suspended inside an oxygen-free high-conductivity copper screen, composed of thin plates (0.1 mm thick) and connected to a cold finger, that is a hollow column filled with liquid nitrogen. The latter plays a crucial role in cooling the screen: thanks to direct contact with the liquid nitrogen bath, the thermal exchange is enhanced, and the cold finger dissipates the heat that accumulates in the screen during the heating cycles more quickly and efficiently than the previous setup.

Once cooled to the temperature of liquid nitrogen, the system uses two heaters mounted on the screen to modulate the temperature of the sample. The heat generated by these heaters is transferred to the sample through radiation, allowing its temperature to be modulated.

Compared to the first version, the results show a clear improvement in the thermal response, along with the elimination of the thermal resistance observed in the previous configuration. However, the modulation time remains quite long (up to 600 seconds) and, consequently, additional improvements need to be made.

4 Simulation results

The radiative heat exchange presents challenges due to the temperature differences between the screen and the sample.

In a thermal cycle based only on radiation, the heating and cooling times of the sample differ significantly. This discrepancy results from the radiative power exchange between the screen and the sample. During heating, the temperature difference between the screen and the sample can be as large as 200 K, allowing for efficient energy transfer. Differently, during cooling, this difference is reduced to only a few tens of Kelvin, resulting in a significant decrease in radiative power exchange and a corresponding increase in cooling time. Even with optimised thermal parameters, these times can differ by more than an order of magnitude.

Various solutions have been explored to address this issue. These include radiators directly coupled to the sample, alternative sample geometries such as switching from a disk to a ring, and the selection of adequate materials [2].

This concept was simulated and analysed using the Finite Element Method. A BSCCO ring-shaped sample (internal radius of 92.0 mm and external radius of 100.0 mm), thermally connected to a graphite radiator sheet ($400.0 \times 400.0 \times 0.1$ mm), is suspended inside a screen heated by a laser beam (power of 10 W). The simulation shows that it is possible to achieve a temperature modulation with a period of about 120 seconds and a temperature amplitude of 3 kelvins.

5 Conclusion

Archimedes will investigate the interaction between quantum vacuum energy fluctuations and the gravitational field, addressing unresolved challenges in modern physics, such as the Cosmological Constant Problem.

A key aspect of this research is the thermal modulation of high-temperature superconductors. Their temperature is modulated around the critical point at very low frequencies (about tens of mHz) with an amplitude of a few Kelvins. This modulation affects the vacuum energy stored within the superconductors, resulting in measurable changes in the gravitational force acting on them. Using a cryogenic and high-precision balance, Archimedes will seek to measure these tiny forces and provide the first experimental evidence of gravity's effect on vacuum energy.

An upgraded thermal modulation system has been set up, and the first promising results have been obtained. Simulations support a mechanically isolated system (consisting of a ring-shaped sample in thermal contact with a radiator) which exchanges heat only with its thermal bath, whose temperature is modulated by a screen that surrounds it.

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