PROCEEDINGS OF SCIENCE

The Archimedes Experiment, results on the thermal modulation system

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The scientific objective of Archimedes is to weigh the vacuum, i.e. to investigate the role of the interaction of vacuum fluctuations with the force of gravity, using a high sensitivity balance. It 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 (thermal modulation). 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 prevent the reversibility of the thermodynamic transformation or generate a spurious force on the sample. A cryogenic prototype at liquid nitrogen temperature is being optimised for performing thermal modulation with the help of a FEM analysis. The characterisation of different high-temperature superconductors is also an important study to be explored. The most recent results will be presented.

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1. Introduction

Archimedes [1] is an experiment of fundamental physics, funded by INFN[1], that will search for weight variations induced by quantum vacuum energy fluctuations. More precisely, it will investigate the potential interaction of these fluctuations with gravity, attempting to shed light on the value of the vacuum energy density. Quantum mechanics predicts a vacuum energy density approximately 120 orders of magnitude larger than what is inferred from cosmological observations. This disagreement is known as the Cosmological Constant Problem [2, 3]. Solving this open problem could deepen the understanding of not only fundamental physics but also the nature of dark energy, the mysterious form of energy identified with vacuum energy and thought to be responsible for the observed accelerated expansion of the universe.

In quantum mechanics, the vacuum is not completely empty but filled with virtual particles that are dynamically created and then destroyed after a very short time, causing continuous vacuum energy fluctuations. These virtual particles are a consequence of Heisenberg's Uncertainty Principle, and their effects are observable and measurable only in specific experimental conditions, such as the in Casimir effect experiments, which study a tiny attractive force between closely spaced parallel conducting plates.

The hypothesis that these vacuum energy fluctuations may interact with gravity results in the vacuum having weight. And the latter may be measured by weighing the vacuum energy stored in a Casimir cavity. If the vacuum weighs, then there is a force exerted by the gravitational field, directed upwards, that acts on the Casimir cavity at rest on Earth, and is equal to the weight of the modes expelled from the cavity, in analogy with Archimedes buoyancy in fluids (hence the name of the experiment) [4]: $\vec{F} = \frac{E_C}{c^2}\vec{g}$. The Casimir energy $E_C = E(a) - E(\infty) = -\frac{\pi^2 \hbar c}{720 a^3} S$ represents the change in energy when the two parallel plates of area S are placed a distance a apart compared to when the plates are infinitely separated ($a \to \infty$).

The Casimir force is sensitive to the electromagnetic boundary conditions created by the plates; therefore, by changing the latter, one could potentially influence the vacuum energy inside the cavity. By way of example, when the plates become superconducting, the reflectivity increases, the vacuum energy contained between the plates is better expelled from the cavity, resulting in a lowering of the energy and, if it gravitates, of the weight [4–6].

The effect of this modulation of vacuum energy is particularly relevant in the context of high-temperature superconductors (high-Tc or HTS), a special class of superconducting materials that can exhibit superconductivity at temperatures much higher than traditional superconductors. These superconductors have a microscopic structure consisting of many superconducting layers separated by dielectric planes and, thus, forming a natural multi-layer Casimir cavity. Archimedes will measure the force due to the variation of the Casimir energy inside this cavity: $\Delta\vec{F} = \frac{\Delta E_C}{c^2}\vec{g}$. For a superconducting disc of diameter 100.0 mm and thickness 5.0 mm, the expected force on it is approximately 5.0×10^{-16} N ($\Delta E_C \sim 4.6$ J) [7, 8].

Therefore, to force a superconductor to enter and exit from the superconducting state and obtain the desired variation of the vacuum energy, a modulation of the temperature of the superconductor around its critical temperature is needed. When the temperature is higher (lower) than the critical

[1]The National Institute for Nuclear Physics (INFN) is the Italian research agency dedicated to the theoretical and experimental research in the fields of subnuclear, nuclear and astroparticle physics (https://home.infn.it/en/).

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temperature, a superconductor has the property of trapping (expelling) vacuum energy that may result in an increase (lowering) of its weight.

2. Balance

A very high sensitivity cryogenic balance based on laser interferometry will measure the small vacuum weight variations induced in superconducting samples. This will be possible by suspending two equal high-temperature superconducting discs at the ends of a balance arm at rest in the gravitational field, and modulating the Casimir energy or temperature only in one of these superconductors. The modulation will generate a periodic force that will act on one end of the measuring arm and make the arm oscillate with the same modulation frequency. The consequent tilt of the measuring arm with respect to the arm of reference will be read using a Michelson interferometer, which will detect variations in the optical path lengths between the two arm ends as a differential signal. A prototype was built to find the best optic-mechanical configuration for the final balance and test each of its components [1, 9].

Archimedes will work at a frequency in the range from about 5 mHz to 10 mHz, and the expected signal is mainly limited by thermal noise and seismic noise. A large cryostat made up of three steel chambers (matryoshka-like configuration) will allow Archimedes to work at cryogenic temperatures. The Experimental Chamber will host the balance and be submerged in liquid nitrogen inside the Nitrogen Chamber (approximately 4000 l). The Insulation Chamber will maintain a high vacuum environment ($\sim 10^{-6}$ mbar) isolating the two inner chambers and the balance from the outside [1]. Archimedes is the first experiment to be installed in the SarGrav underground laboratory[2], in the area of the disused Sos Enattos mine in Sardinia (Italy). Thanks to the unique geological properties of Sardinia and the low population density, Sos Enattos area is an excellent site to host experiments that require very low seismic noise levels. Being one of the quietest places in Europe, it is also a perfect candidate to host the third generation gravitational wave observatory Einstein Telescope [10–12].

3. Thermal Modulation

The temperature of a superconductor has to be modulated around its critical temperature using only the radiation heat transfer. This mechanism allows the thermal energy to be added to or removed from the sample through electromagnetic radiation. In this way, the sample is isolated from any external interaction that could inject other energy with respect to the one needed to perform the reversible transformation.

A first cryogenic vacuum system has been built to modulate the temperature of a YBCO disc (diameter of 100.0 mm and thickness of 3.0 mm) in a liquid nitrogen bath (77.0 K) switching a cartridge heater (40 W) on and off. The system operated under a vacuum with a pressure of approximately 10^{-5} mbar. The disc was surrounded by a copper screen and suspended using low conductivity thin wires to thermally insulate it from the system. Nevertheless, once the heater was turned off, the temperature of the screen did not decrease according to the time constant expected

[2]The SarGrav laboratory has both surface and underground facility, and is dedicated to the research on gravitational waves, gravitational physics and geophysics.

from thermal conduction, and the temperature of the sample could not be modulated at a few tens of mHz with a maximum amplitude of three K around its critical temperature, as required by Archimedes.

The conclusion drawn from Finite Element Method simulations (FEM) is that there is a significant thermal resistance between the support of the screen and the base of the Experimental Chamber in which the system is placed. This resistance affects how quickly the screen returns to its initial temperature after the heater is turned off, making the modulation frequency well below 10 mHz, and causes radiation heat transfer to become the dominant mechanism. Moreover, this heat transfer through radiation between sample and screen is not efficient if a disc-shaped sample is used.

An upgraded cryogenic vacuum system is currently under construction to eliminate this thermal resistance and enhance the heat exchange between system and liquid nitrogen bath. The main changes involve reducing the thickness of the base of the experimental chamber, utilising Oxygen-Free High Conductivity (OFHC) copper to have a higher thermal conductivity, black-coating the internal surface of the screen to increase the emissivity between sample and screen, reducing the number of parts connected with screws, and anchoring the screen support to a hollow column filled with liquid nitrogen.

Given that HTS materials have low thermal conductivity, changing the geometry of the sample, from a disc to a ring, may help reduce thermal gradients between the centre and the periphery of the sample. And this may result in a more uniform temperature distribution and potentially faster temperature modulation. To improve this even more, the ring-shaped sample may be in thermal contact with a thin foil (made of aluminium, silver, or graphite) used as a radiator. Sample and radiator form a mechanically isolated system that exchanges heat only with its thermal bath whose temperature is modulated by the screen that surrounds this system. During the heating phase, the sample absorbs heat through radiation, and this heat is then transferred to the radiator through conduction. The radiator radiates heat more rapidly than the sample can do on its own, accelerating the cooling process. Such a system was analysed using FEM (Figure 1 of the Appendix).

A BSCCO ring-shaped sample (internal radius of 92.0 mm, external radius of 100.0 mm and volume of 20.0×10^3 mm^3) is positioned on one side of a graphite radiator sheet ($400.0\times400.0\times0.1$ mm). In the heating phase, the screen is heated by a laser beam incident on its external surface ($500.0 \times 100.0 \times 0.1$ mm) with a power of 10 W. The heat from the screen is then transferred to the system sample-radiator through radiation. The cooling phase begins when the laser beam is switched off. Cooling is facilitated by a cold finger in thermal contact with the screen. The base of the cold finger is maintained at a fixed temperature of 70.0 K. The simulation demonstrates that a thermal modulation with a period of approximately 120 seconds (close to 10 mHz) and an amplitude of 3 K is indeed achievable. Despite the need for further parameter optimisation, these results are encouraging and support the concept of a mechanically isolated system that includes a ring-shaped sample in thermal contact with a radiator.

Simulations and analyses are ongoing, and the upgraded system will allow the Archimedes collaboration to test different solutions and determine the most effective one. The results of these studies will play a crucial role in shaping the final design of the temperature control and modulation system that will be integrated into Archimedes' balance.

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4. Samples

Measuring significant variations in vacuum weight requires massive (mass > 200.0 g) and uniform superconducting samples (critical temperature > 80.0 K and superconducting transition width ≤ 2.0 K). Manufacturing high-quality and very large HTS superconductor samples is challenging due to the complexity of their crystal structures and the need for precise control over their properties. Archimedes collaborates with CAN Superconductors[3], a European manufacturer of superconducting bulk materials and components, for getting custom-made samples that meet the specific requirements of the experiment.

YBCO was the first HTS material to be tested by the Archimedes team, because of its high critical temperature (92.0 K [13]) and because it is one of the most studied HTS superconductors. As YBCO single crystals of the required dimensions are not currently available, discs made from sintered powders were used. In collaboration with CAN Superconductors, the sintering and annealing temperatures as well as the annealing oxygen pressure were modified to optimise the critical temperature and the transition width. However, due to the unavoidable formation of spurious phases during the sintering process, it was not possible to reach transition widths smaller than 3 K (Figure 2 of the Appendix).

The results obtained from YBCO led to the decision to focus on single crystal GdBCO samples. Two fragments of such a superconducting material were studied, showing a higher critical temperature equal to 93.5 K and a narrower and well-defined transition width of about 1.0 K (Figure 2 of the Appendix).

A third possibility is to use sintered BSCCO 2223 samples, in order to compensate the large transition with an higher critical temperature (around 107.0 K [13]). For this reason, some samples of BSCCO have been bought and will be studied shortly. The ability to easily shape sintered BSCCO into ring-shaped samples, combined with its higher critical temperature, makes it a potential and promising candidate, together with GdBCO, for the sample of the Archimedes experiment. The final material choice will depend on the specific size and shape required for the sample.

5. Conclusion

The interplay between Quantum Mechanics and General Relativity is complex, and reconciling these two theories is a challenge in modern physics. Various approaches have been proposed to address the Cosmological Constant Problem, but it remains a topic of ongoing research and debate. Exploring the role of quantum vacuum energy fluctuations and their interaction with gravity may solve this open problem and provide insights into the nature of dark energy and the cosmic acceleration. Archimedes will be the first experiment to prove or disprove the gravitational interaction of vacuum energy by measuring the force that the gravity exerts on a superconductor (natural multi-layer Casimir cavity). This interaction will be measured using an extremely sensitive cryogenic balance and modulating the temperature of superconductors like GdBCO or BSCCO at very low frequencies (about tens of mHz). Archimedes will also make accurate measurements of the background noise of the Sos Enattos area in Sardinia to confirm the suitability to host the Einstein Telescope gravitational wave observatory.

[3]https://www.can-superconductors.com

A. Appendix

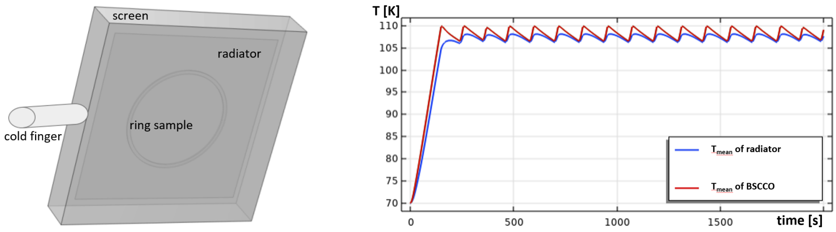

Figure 1: Left – Mechanically isolated system composed of a ring-shaped sample in thermal contact with a radiator inside a screen. Right – Modulation of temperature of a BSCCO ring-shaped sample between 107.0 K and 110.0 K at the frequency of 8 mHz (120 s).

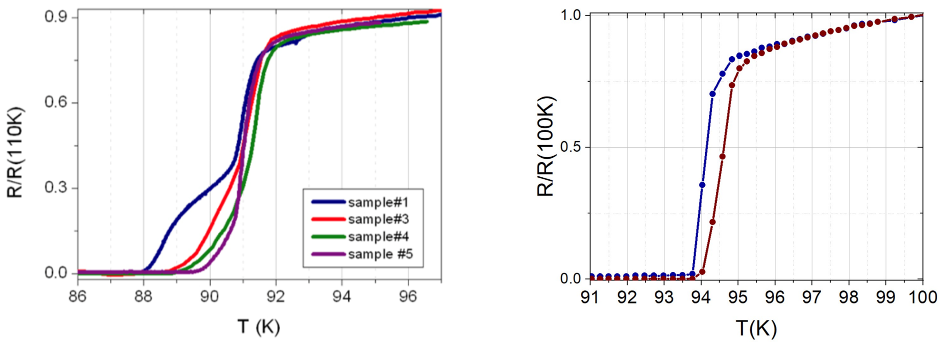

Figure 2: Electrical resistance as a function of the temperature curves for sintered YBCO (left) and single crystal GdBCO (right) superconducting samples. Left – Several sintered YBCO samples made by changing the sintering and annealing temperature and annealing oxygen pressure were tested. These changes led to a significant reduction in the transition width, going from ΔT_c = 3.5 K for sample 1 to ΔT_c = 2.0 for sample 5. However, spurious and/or oxygen deficient phases could not be avoided, as indicated by the presence of two slopes in all the R vs T curves. Right – A narrow transition width suggests a remarkable uniformity.

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