VIP

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1 The VIP scientific case and the experimental method

Within VIP a high sensitivity experimental test on the Pauli Exclusion Principle for electrons is being performed, together with other tests on fundamental physics principles.

The Pauli Exclusion Principle (PEP), a consequence of the spin-statistics connection, plays a fundamental role in our understanding of many physical and chemical phenomena, from the periodic table of elements, to the electric conductivity in metals and to the degeneracy pressure which makes white dwarfs and neutron stars stable. Although the principle has been spectacularly confirmed by the huge number and accuracy of its predictions, its foundation lies deep in the structure of quantum field theory and has defied all attempts to produce a simple proof. Given its basic standing in quantum theory, it is appropriate to carry out high precision tests of the PEP validity and, indeed, mainly in the last decades, several experiments have been performed to search for possible small violations. Many of these experiments are using methods which are not obeying the so-called Messiah-Greenberg superselection rule (MG). Moreover, the indistinguishability and the symmetrization (or antisymmetrization) of the wave-function should be checked independently for each type of particles, and accurate tests were and are being done.

The VIP (VIolation of the Pauli Exclusion Principle) experiment, an international Collaboration among 10 Institutions of 6 countries, has the goal to either dramatically improve the previous limit on the probability of the violation of the PEP for electrons, ($\beta^2/2 < 1.7 \text{ x } 10^{-26}$ established by Ramberg and Snow: *Experimental limit on a small violation of the Pauli principle*, Phys. Lett. **B 238** (1990) 438) or to find signals from PEP violation.

The main experimental method consists in the introduction of electrons into a copper strip, by circulating a DC current, and in the search for X-rays resulting from the forbidden radiative transition that occurs if some of the new electrons are captured by copper atoms and cascade down to the 1s state already filled by two electrons with opposite spins (Figure 1).

The energy of the 2p $\rightarrow$ 1s transition would differ from the standard K_α transition by about 300 eV (7.729 keV instead of 8.040 keV) providing an unambiguous signal of the PEP violation. The measurement alternates periods without current in the copper strip, in order to evaluate the X-ray background in conditions where no PEP violating transitions are expected to occur, with periods in which current flows in the conductor, thus providing "new" electrons, which might violate PEP.

The goal of VIP-2 *Open Systems*, due to the peculiarity to introduce new fermions (current) in a pre-existing system of identical fermions, is to establish the strongest bounds on $\beta^2/2$ obeying the Messiah-Greenberg superselection rule.

A new class of theoretical predictions, in the context of Quantum Gravity and CPT deformation, recently emerged, predicting PEP violation at high energy scales. These models violate Messiah-Greenberg and can be tested with closed systems, i.e. without current. The VIP-2 *Closed Systems* experimental setups are based on extreme radio-purity targets and high purity Germa-

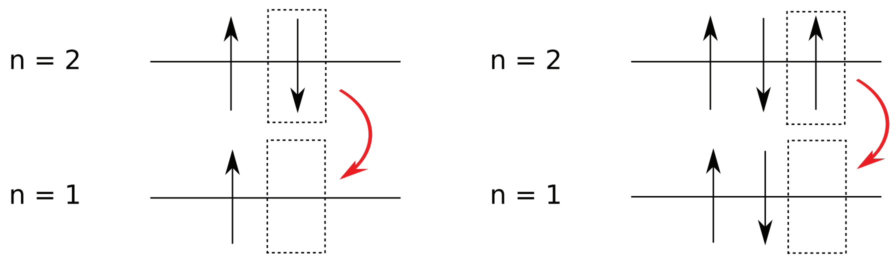

Figure 1: *Normal 2p to 1s transition with an energy around 8 keV for Copper (left) and Pauli-violating 2p to 1s transition with a transition energy around 7.7 keV in Copper (right).*

nium detectors. Our goal is to improve the current limits on the new-physics emergence scale, in a regime which is not accessible to current accelerator experiments, thus providing fundamental down-top constraints to the models.

The VIP collaboration has extended its scientific program to the study of other issues in fundamental physics, such as models of spontaneous wave function collapse. The Continuous Spontaneous Localization (CSL) and the Diosi-Penrose (DP) models consist in non-linear and stochastic modifications of the Shrödinger equation, which induce the wave function collapse with a strength which is proportional to the collapsing quantum state' mass. In both models the collapse is related to unavoidable emission of a characteristic *spontaneous radiation*, which is not present in standard quantum mechanics. We refer to the previous activity reports for more details. The analysis of the data we collected with a dedicated setup, based on a High Purity Germanium detector, lead us to falsify the DP model in its present formulation [1]. We also set the most stringent constraints on the CSL model, in a broad range of the parameters space [2] [3]; in particular we constrained, for the first time, the correlation length r_C above the value $r_C = 10^{-7}$ m predicted by the Ghirardi-Rimini-Weber model [4]. New studies are presently ongoing, aimed to challenge generalized versions of the models, and to investigate the recently developed prediction of spontaneous collapse emerging in Quantum Gravity context.

2 The VIP and VIP-2 Open Systems setups

The first VIP setup was realized in 2005, starting from the DEAR setup, reutilizing the CCDs (Charge Coupled Devices) as X-ray detectors, and consisted of a copper cylinder, were current was circulated, 4.5 cm in radius, 50 μm thick, 8.8 cm high, surrounded by 16 equally spaced CCDs of type 55.

The CCDs were placed at a distance of 2.3 cm from the copper cylinder, grouped in units of two chips vertically positioned. The setup was enclosed in a vacuum chamber, and the CCDs cooled to 165 K by the use of a cryogenic system. The VIP setup was surrounded by layers of copper and lead to shield it against the residual background present inside the LNGS laboratory, see Figure 2.

The DAQ alternated periods in which a 40 A current was circulated inside the copper target with periods without current, representing the background.

VIP was installed at the LNGS Laboratory in Spring 2006 and was taking data until Summer 2010. The limit on the probability of PEP violation was found to be: $\beta^{\,2}/2 < 4.6 \times 10^{29}$.

In 2011 we started to prepare a new version of the setup, VIP-2 Open Systems, for which a first version was finalized and installed at the LNGS-INFN in November 2015. The aim of the experiment is to improve the limit on $\beta^{\,2}/2$ of at least other two orders of magnitude.

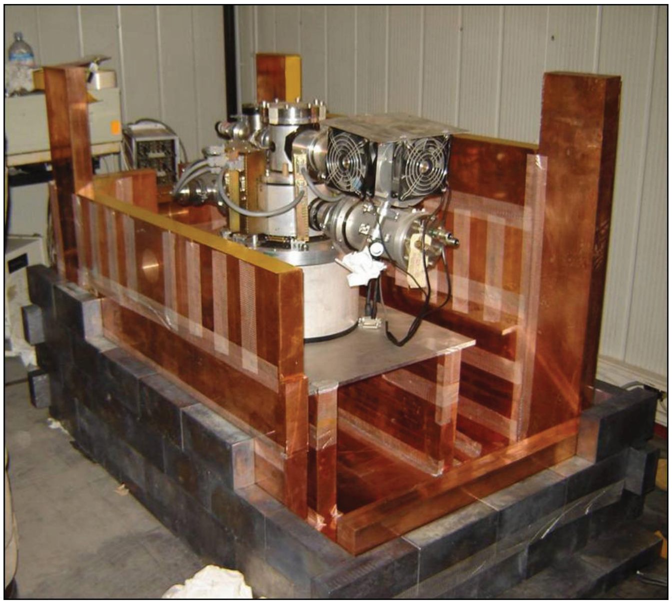

Figure 2: *The VIP setup at the LNGS laboratory during installation.*

The goal of the VIP-2 experiment is to improve by at least two orders of magnitude the result obtained by the previous VIP measurement ($\beta^2/2 < 4.7 \times 10^{-29}$ 13)).

In 2018 the VIP2 setup was upgraded with new SDDs and shielding, which was completed in 2019.VIP-2 collected about three years of data in the period April 2019 - May 2024, alternating periods with and without current circulating in the target.

2.1 VIP-2 Open Systems - a new high sensitivity experiment

In order to achieve a signal/background increase which allows a gain of two orders of magnitude for the probability of PEP violation for electrons, a major upgrade of the experimental setup was done and a refined scheme for the statistical interpretation of the data was used. Also an advanced model of the current electrons propagation and interaction inside the target is under development.

The main improvements of the experimental apparatus consisted in:

- the replacement of the charged coupled devices for the X-rays detection, with state-of-the-art, 450 μm thick, Silicon Drift Detectors (SDDs), characterized by a higher energy resolution (190 eV (FWHM) at 8 keV), large geometrical acceptance and an efficiency of 99% at 8 keV,
- a more compact and thinner target ensuring higher acceptance and efficiency,
- a new cooling system of the copper target, which allowed to enhance the circulating current to a peak value of 200 A (with respect to the 40 A of VIP).

The final configuration of the experiment was finalized in early 2019, with four arrays of 2×4 SDD cells surrounding the target. Two sections of the VIP-2 vacuum chamber, with the details of the inner components of the setup, are shown in Fig. 3. The whole system is enclosed in an external shielding complex (an outer lead layer surrounding an internal copper layer), aimed to provide further suppression of the environmental radiation from the underground rocks.

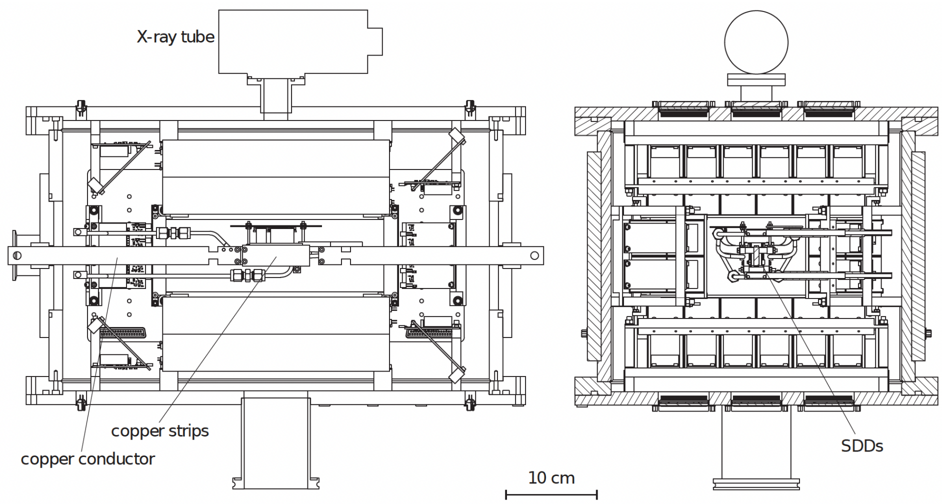

Figure 3: The lateral (left) and front (right) sections of the vacuum chamber and the inner components of the VIP-2 apparatus.

From the viewpoint of the data interpretation, simultaneous with the final setup completion, a series of new data analyses methods were optimized. Among these, some are concerning new concepts in testing the Pauli exclusion principle in bulk matter, accounting for the random walk of the electrons in the target and semi-analytical Monte Carlo methods to simulate the signal [5, 6]. Moreover, new calibration techniques have significantly enhanced the experiment's capabilities. These techniques leverage Machine Learning and Differentiable Programming algorithms [20, 21], leading to an improvement in the SDDs' energy resolution to 180 eV (FWHM) at 8 keV, a gain of approximately 10 eV over the previous state-of-the-art resolution.

3 VIP-2 Open Systems Activities in 2024, preparation of the future VIP-3 setup

In 2023 a complex renovation activity of the setup was performed:

- the target cooling system was rebuilt and installed,
- the current feedthrough was substituted with a safer one, made of super flexible Cu cables of 50 mm^2 section,
- these interventions allowed to increase the circulating current from 180 A to 200 A,
- vacuum instability problems of the chamber were solved, and 2 orders of magnitude were gained in pressure (from $7 \cdot 10^{-5}$ mb to $6 \cdot 10^{-7}$ mb),
- some non performant SDDs were substituted.

The data taking restarted in September 2023 and last until May 2024, alternating periods with and without current circulating in the target. The calibrated and normalized spectra are shown in Figure 4.

The whole statistics of the VIP-2 acquired data, before the shut down due to the shack renovation (see the previous report), was analyzed and produced the strongest upper bounds on the PEP violation probability respecting MG. Two, complementary, analysis frameworks were

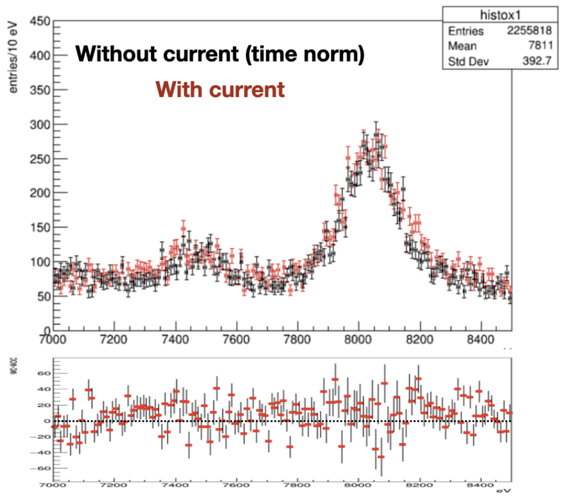

Figure 4: *The calibrated and normalized data are shown, for the two data taking configurations with and without current circulating in the Cu target, in the period September 2023 - January 2024.*

followed, a Bayesian statistical model and a frequentist Confidence Levels (CL_s) approach, which share the same spectral shape description for the signal and the control spectra (without current). A detailed discussion of analyses methods is presented in Ref. [14]. The two approaches result in the following upper limits on the PEP violation probability for electrons in copper:

$$\beta^2/2 \leq 3.16 \times 10^{-31} \text{ (Bayesian)} \qquad \beta^2/2 \leq 3.29 \times 10^{-31} \text{ (CL}_s\text{)}, \tag{1}$$

when the electrons propagation in the target is described by means of an electron diffusion model, i.e. the number of electron-atom interactions is obtained from the ratio of the target length and the electrons scattering length in copper.

According to more realistic diffusion models which we developed [5, 15], electron-atom interactions in copper occur over a characteristic time $\tau = 3.3 \times 10^{-17}$ s, therefore significantly increasing the number of independent PEP tests performed by each current electron, leading to the enhanced limits:

$$\beta^2/2 \leq 2.47 \times 10^{-43} \text{ (Bayesian)} \qquad \beta^2/2 \leq 2.57 \times 10^{-43} \text{ (CL}_s\text{)}. \tag{2}$$

3.1 VIP-2 in current modulation regime

In the period October-December 2020 an exploratory data taking in current modulated regime was performed, for a period of about 68 days. The with-without (wc-woc) current alternation was automatized with a fixed period of 100 s: 50 s of wc phase alternated to 50 s woc. A novel data analysis framework was developed in Ref. [16] which consists in a simultaneous spectral and discrete Fourier transform Bayesian analysis. This novel approach leads to a 32% reduction of the 0.9 probability constraint on the PEP violating signal.

This work was a pathfinder for the following data taking campaigns, indeed the current modulation regime was exploited in the last phase of VIP-2, and it will be adopted in the future VIP-3-Hybrid and VIP-3 data taking runs. The analysis of the whole current modulation data set is being finalized and the related paper is in preparation.

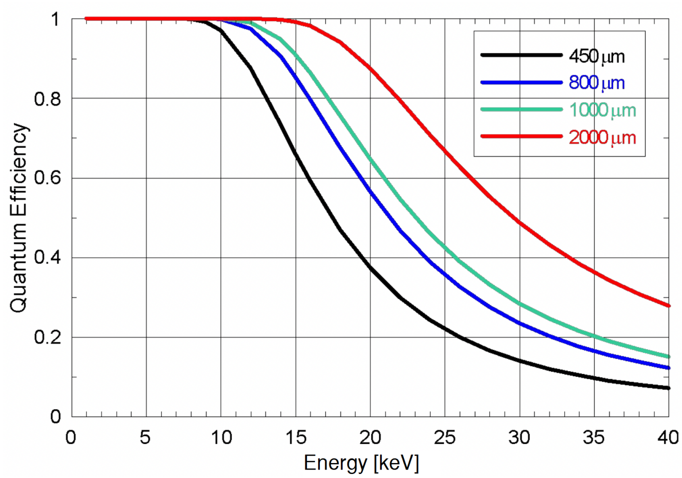

Figure 5: The figure shows the quantum efficiency as a function of the energy, for SDD devices of various thicknesses. The black curve corresponds to the detectors currently used in VIP-2, the green curve shows the efficiency achievable with the new 1 mm thick SDDs which we are presently developing for the VIP-3 experiment (reported from [18]).

3.2 from VIP-2 to VIP-3-Hybrid

The future perspective of the VIP Open Systems experiments is a scan of the $\beta^2/2$ limits over selected elements, in order to perform a systematic test of the PEP validity in the atomic transitions, over the periodic table. The main technical challenge in testing materials characterized by a higher atomic number (Z) than copper, is given by the reduction of the SDD detectors quantum efficiency as a function of the increasing energy. To overcome this problem VIP is collaborating with Fondazione Bruno Kessler (FBK, Italy) and Politecnico di Milano (PoliMi, Italy), for the development of new cutting edge SDD detectors characterized by double thickness, with respect to the standard detectors used in the VIP-2 experiment (1 mm versus 0.45 mm).

Taking advantage of the fact that two arrays of 1 mm thick SDDs (out of the eight which will be employed in VIP-3) have been already produced and tested, a VIP-3-Hybrid setup will be operated in 2025, during the transition towards the complete VIP-3 setup. The realization of VIP-3-Hybrid is under finalization. The setup will be hosted in the re-adapted VIP-3 vacuum chamber (already realized), and will employ two arrays of 1mm thick SDDs together with 2 of the old ones (450um). VIP-3 Hybrid will allow to perform a characterization of the background with the new chamber, and to make an assessment of VIP-3 performance in known (ideal) conditions (e.g. characterization and energy calibration of the 1mm thick SDDs).

3.3 VIP-3 Open Systems

The VIP-3 Open Systems experiment aims to perform a search of the PEP violating atomic transitions over Z up to targets with atomic numbers as high as $Z \sim 50 - 60$ (e.g. silver, tin, palladium, zirconium), with a sensitivity comparable to VIP-2. Tests performed on the already finalized 1 mm thick SDDs demonstrated, that the quantum efficiency of the new SDDs is roughly double (with respect to the standard detectors), in the energy range $(20 - 25)$ keV (characteristic of the $K_{\alpha_{1,2}}$ transitions in the new targets); while the energy resolution remains constant. The quantum efficiency is shown in Fig. 5.

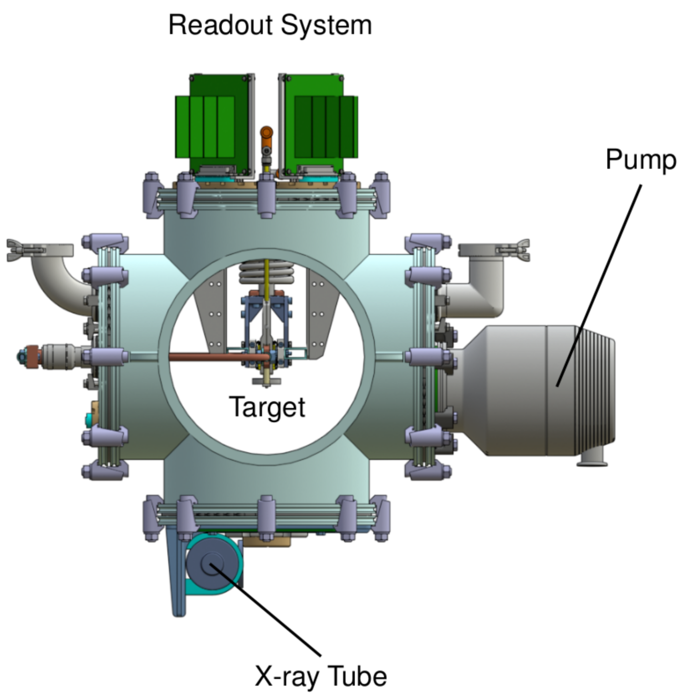

Figure 6: The VIP-3 Setup is shown, in particular the VIP-3 vacuum chamber, where the pump, X-ray tube, readout electronics, and target are highlighted. The front and rear flanges are removed to show the inner components.

The VIP-3 inner configuration will consist of 8 SDD arrays, facing two target strips, where the direct current will be circulated. With respect to the 4 SDD arrays used in VIP-2, VIP-3 will exploit a total of 64 SDD cells, for a double active area of about 41 cm^2, in order to increase the geometrical efficiency. A new thermal contact will be realized, between the cold-finger and the SDD detectors, made of pure copper to minimize the natural copper radio-contamination. A new target cooling system will also be built made of pure copper. With respect to the steel thermal contact and cooling system used in VIP-2, the new copper structures will introduce a further advantage. Copper is characterized by almost one order of magnitude higher thermal conductivity with respect to steel. This will reduce the detectors working temperature (improving the energy and timing resolution) and will also increase the applicable maximum current circulating in the target (from the 200 A peak current of VIP-2 up to 400 A). The introduced improvements compensate the quantum efficiency reduction, from 8 keV up to 25 keV, thus keeping at least constant the sensitivity of the experiment. The design of the VIP-3 setup is shown in Fig. 6.

Details on the progress of the VIP-3 setup preparation and on the calculation of the PEP violating transition energies, by means of a multi-configuration Dirac-Fock for general matrix elements code, are presented in Refs. [17, 18].

The possibility to extend the scan of the limits on $\beta^2/2$ for elements characterized by atomic numbers in the range $Z \sim 60 - 70$ is under study. This would require a further leap in the quantum efficiency of the detectors. To this end layered structures of 1 mm thick SDDs are under investigation.

Based on a preliminary data analysis, an improvement of about two orders of magnitude on the upper limit of $\beta^2/2$, with respect to Ref. [8], was estimated for a four months data taking, and a circulating current of 400 A.

4 VIP-2 Closed Systems Activities in 2024

The VIP Closed Systems experimental activity is realized in collaboration with the Low Radioactivity Laboratory at LNGS (team lead by Matthias Laubenstein). In particular, the experimental setup which was used to set bounds on NCQG models is based on a high purity co-axial p-type germanium detector (HPGe), with a diameter of 8.0 cm and a length of 8.0 cm, surrounded by an inactive layer of lithium-doped germanium of 0.075 mm. The active germanium volume of the detector is 375 cm^3. The target material is composed of three cylindrical sections of radio-pure Roman lead, fully surrounding the detector. The thickness of the target is about 5 cm, for a total volume $V \sim 2.17 \times 10^3$ cm^3. The inner part of the setup is shown in Fig. 7. A detailed description of the external passive shielding complex, the cryogenic and vacuum systems, as well as of the data acquisition system is given in Refs. [19].

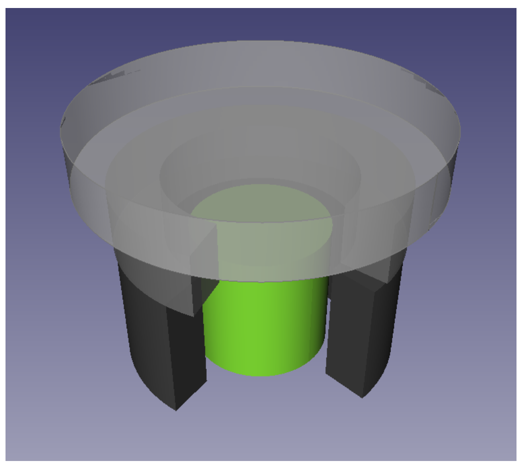

Figure 7: Schematic representation of the Ge crystal (in green) and the surrounding lead target cylindrical sections (in grey).

The aim of the measurement was to search for the X-rays signature of PEP-violating K$_\alpha$ and K$_\beta$ transitions in Pb, when the 1s level is already occupied by two electrons. The analysis strategy consisted in extracting the upper limit $\bar{S}$ of the expected number of total signal counts, generated by PEP violating K$_\alpha$ and K$_\beta$ transitions in the target. A Bayesian comparison of $\bar{S}$ with the theoretically expected photons emission, due to PEP violating atomic transitions, then provided a limit on the scale Λ of the model. A phenomenological model was developed, for the analysis of the data set collected with a High Purity Germanium detector and a high radio-purity Roman lead target. The analysis lead to the strongest bounds on the θ-Poincaré model [9], to exclude the model k-Poincaré in the Arzano-Marcianò Quantization procedure, and to set the first constraint to the "triply special relativity" model proposed by Kowalski-Glikman and Smolin. The characteristic energy scale of the model is bound to $\Lambda > 5.6 \cdot 10^{-9}$ Planck scales [10].

The investigation of anisotropy effects, induced by Quantum Gravity effects on the PEP violating transition amplitudes is in an advanced state. The calculation of the amplitude is under finalization, and the study of a dedicated setup is ongoing.

An exploratory measurement is currently ongoing, based on a Broad Energy Germanium detector (BEGe), which is aimed to improve our current limits by testing PEP violating K_α transitions in Ge, thus exploiting the much higher detection efficiency, with respect to events generated in the Roman Pb target. The following activities were performed:

- Two new runs of data taking were performed (for a total of about seven months).
- The development of the dedicated pulse shape discrimination algorithm, deep convolutional neural network based, was finalized. The algorithm discriminates single site from multi-site events, with a classification accuracy of over 95%.
- The analysis of the collected data reveals the presence of a microphonic background, which dominates the low-energy region and requires a low-energy cut at about 13 keV.
- Considered that the investigation of PEP violating K_α transitions in Ge requires a lower energy threshold of few keV, two accurate measurements of the microphonic noise, in the low radioactivity hosting lab, wer performed in collaboration with Ing. Tomassini from LNF -INFN, aimed to test the microphonic background under different environmental conditions. The measurement was performed using two geophones and two accelerometers. As an example, the displacement power spectral density measured by one of the accelerometers is shown in Figure 8. Prominent peaks are found at about 50 Hz, 100 Hz and 180 Hz.
- The measurement of the microphonic background was used for optimizing the design of an isolation system, consisting of pneumatic isolators and a soundproof box, which will lead to a suppression of the microphonic noise of a factor greater than 10, thus allowing to reach the desired lower energy threshold.

One paper reporting the activity on the BEGe detecor system was published in Condens. Mat. 9 (2) (2024), 22. The realization of the isolation system is under completion. The upgraded setup will be installed in the Low Radioactivity Laboratory within spring 2025.

5 Collapse Models experimental/phenomenological activity 2024

During 2024, in collaboration with leading theoretical groups in this field (e.g. Lajos Diosi Eotvos Univ., Angelo Bassi Trieste Univ. and S. Donadi Queen's University Belfast) the spontaneous electromagnetic radiation from atomic systems, induced by dynamical wave-function collapse, was investigated in the x-ray domain. Strong departures are evidenced with respect to the simple cases considered until now in the literature, in which the emission is either perfectly coherent (protons in the same nuclei) or incoherent (electrons). In this low-energy regime the spontaneous radiation rate strongly depends on the atomic species under investigation and, for the first time, is found to depend on the specific collapse model.A paper reporting these results was published in Phys.Rev.Lett. 132 (25) (2024) 250203. On the basis of the expertise achieved by the group in the development of detectors based on germanium detectors, we are studying a dedicated detector, which is able to reveal this effect, in the range (1-15) keV, and to simultaneously test quantum gravity models that also predict wave function collapse.

6 Events organization in 2024

In 2025 the following events related to the physics of VIP, and, more generally to quantum mechanics, were organized:

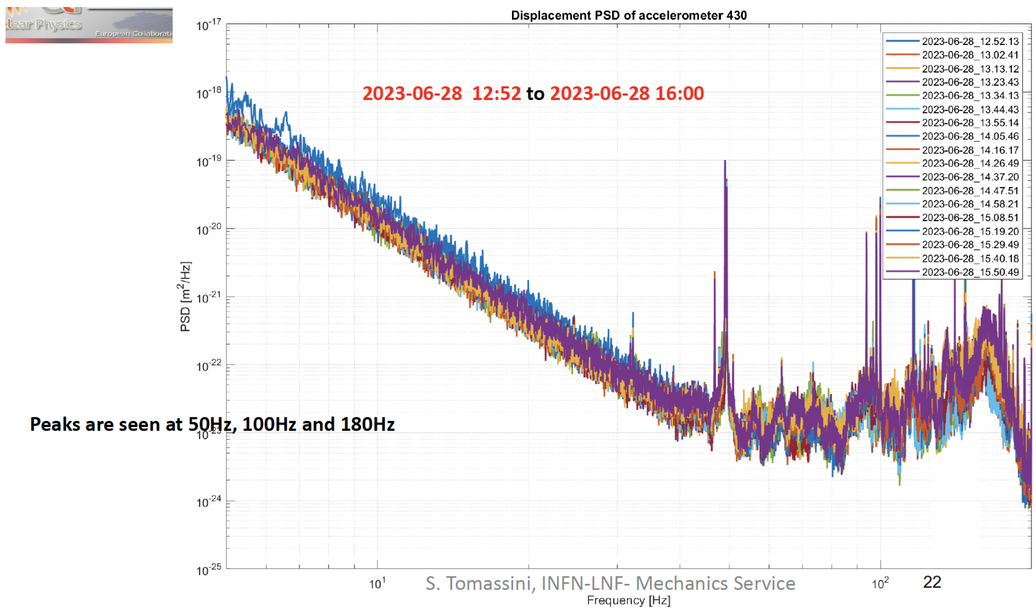

Figure 8: *Displacement power spectral density measured by one of the accelerometers in the laboratory which hosts the BEGe based setup. (reported from* [22]*).*

- A Modern Odyssey: Quantum Gravity meets Quantum Collapse at Atomic and Nuclear physics energy scales in the Cosmic Silence, 3-7 June 2024, ECT* Trento (Italy),

  https://indico.ectstar.eu/event/207/timetable/20240603/

- Exploring the Quantum Boundaries: an Odyssey into the gravity related collapse models INFN-LNF, Frascati, 12-14 June 2024, https://agenda.infn.it/event/40188/

- Quantum Optics, Gravity, and Collapse: Charting New Phenomenological Horizons, 25th October 2024, Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi" Rome (Italy)

  https://www.cref.it/eventi/workshop-on-quantum-optics-gravity-and-collapse

- Exploring the Quantum Boundaries: an Odyssey into the gravity related collapse models INFN-LNF, Frascati, in mixed modality (presence and online), 12-14 June 2024,

  https://agenda.infn.it/event/40188/

7 Activities in 2025

It follows a schematic description of the activities which will be performed during 2025:

- The VIP-3-Hybrid setup will be installed at LNGS within spring 2025 and will take data for optimizing the setup. In parallel the full VIP-3 setup realization will be finalized. VIP-3 will be installed at LNGS within early 2026, and the data taking will start in current modulation regime.

- The upgraded BEGe based setup will be installed at LNGS within spring 2025. A data taking period of 2/3 months will be performed.
- The data analyses (from both HPGe and BEGe detector based setups) will be refined, in the contexts of beyong STandard Model Physics, such as Non Commutative Quantum Gravity, Generalized uncertainty principle and CPT deformation induced PEP violation.
- We will continue the investigation of experimental signatures of models of dynamical wave function collapse. Based on the expertise acquired in the optimization of germanium based detector systems, we will design an experiment dedicated to the simultaneous measurement of quantum gravity and quantum collapse signals.
- Other studies related to Quantum Foundations (such as J-PET and Quantum Biology) will be continued.

Acknowledgements

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We acknowledge support from the Centro Ricerche Enrico Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi" (Open Problems in Quantum Mechanics project).

8 List of Conference Talks by LNF Authors in 2024

1. F. Napolitano, "Testing the Pauli Exclusion Principle and Fundamental Symmetries in Underground Experiments", DISCRETE 2024, Ljubljana (SI), 04/12/24.
2. F. Napolitano, "Machine Learning with the VIP-2 experiment", "Exploring Quantum Boundaries" Frascati (IT) 13/06/24.
3. F. Napolitano, "ML and differentiable programming optimization for X-Ray experiments", at ECT* Trento Bridging Scales Workshop, Trento (IT) 15/04/2024
4. F. Sgaramella, "Silicon Drift Detectors in Modern Quantum Experiments: Investigating the Pauli Exclusion Principle", A Modern Odyssey: Quantum Gravity meets Quantum Collapse at Atomic and Nuclear physics energy scales in the Cosmic Silence, 3-7 Giugno 2024, TRENTO (ECT*)
5. F. Sgaramella, "Silicon Drift Detectors in Modern Quantum Experiments: Investigating the Pauli Exclusion Principle", Exploring the Quantum Boundaries: an Odyssey into the gravity-related collapse models, 12-14 Giugno 2024, Frascati.
6. N. Bortolotti, "Testing quantum foundations in high sensitivity X-ray experiment at LNGS", Quantum optics, gravity and collapse: charting new phenomenological horizons, 25 Ovtober 2024, CREF, Rome, Italy.

7. N. Bortolotti, “Phenomenological exploration of the interplay between gravity and quantum mechanics”, Sapienza’s Phd seminars, 18 Octiber 2024, Rome, Italy.

8. N. Bortolotti, “Probing spacetime non-commutativity and GUP through Pauli exclusion principle tests”, 13th Young Researcher Meeting, 25 September 2024, Palermo, Italy.

9. N. Bortolotti, “Probing quantum gravity through high sensitivity spin-statistics tests”, Exploring the Quantum Boundaries: an Odyssey into the gravity-related collapse models, 13 June 2024 , LNF, Italy.

10. N. Bortolotti, ”Probing quantum gravity through high sensitivity spin-statistics tests”, A Modern Odyssey: Quantum Gravity meets Quantum Collapse at Atomic and Nuclear physics energy scales in the Cosmic Silence, 03-07 June 2024, ETC* Trento, Italy

11. K. Piscicchia, “Phenomenological investigation of the interplay among Quantum and Gravity at LNGS, an overview”, A Modern Odyssey: Quantum Gravity meets Quantum Collapse at Atomic and Nuclear physics energy scales in the Cosmic Silence, 3-7 June 2024, ECT* Trento, Italy.

12. K. Piscicchia, “Phenomenological investigation of the interplay among Quantum and Gravity at LNGS, an overview”, Exploring the Quantum Boundaries: an Odyssey into the gravity-related collapse models, 12-14 June 2024 INFN-LNF, Frascati, Italy.

13. K. Piscicchia, “Phenomenological Investigation of Quantum Foundations at LNGS”, Institute of Optics (CNR), 24 June 2024, Pozzuoli, Napoli, Italy.

14. S. Manti, “ Cancellation Effects in the Spontaneous Collapse Rate at Low Energy Limit”, A Modern Odyssey: Quantum Gravity meets Quantum Collapse at Atomic and Nuclear physics energy scales in the Cosmic Silence, 03-07 June 2024, ECT*, Trento, Italy.

15. S. Manti, “Cancellation Effects in the Spontaneous Collapse Radiation Rate at Low Energy Limit”, Exploring the Quantum Boundaries: an Odyssey into the gravity-related collapse models, 12–14 June 2024 Laboratori Nazionali di Frascati, Italy.

16. S. Manti, “Testing the Pauli Exclusion Principle across the periodic table with the VIP-3 experiment”, SIF 2024, Bologna, Italy.

17. C. Curceanu, “From exotic atoms at accelerators to testing quantum foundations underground”, Colloquium, Melbourne University, 10th December 2024, Australia.

18. C. Curceanu, “Testing quantum mechanics in the Cosmic Silence Quantum Collapse and Pauli Exclusion Principle”, World Quantum Days in IFIN-HH, 15-18 April 2024, Bucharest, Romania.

9 Publications in 2024

1. Simone Manti, Massimiliano Bazzi, Nicola Bortolotti, Cesidio Capoccia, Michael Cargnelli *et al*, Testing the Pauli Exclusion Principle across the Periodic Table with the VIP-3 Experiment, Entropy 26 (2024) 9, 752.

2. L. Baudis, R. Biondi, A. Bismark(Zurich U.), A. Clozza, C. Curceanu *et al*, Search for Pauli Exclusion Principle violations with Gator at LNGS, Eur.Phys.J.C 84 (2024) 11, 1137, e-Print: 2408.02500 [nucl-ex].

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