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, ($\beta^2/2 < 1.7$ 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-

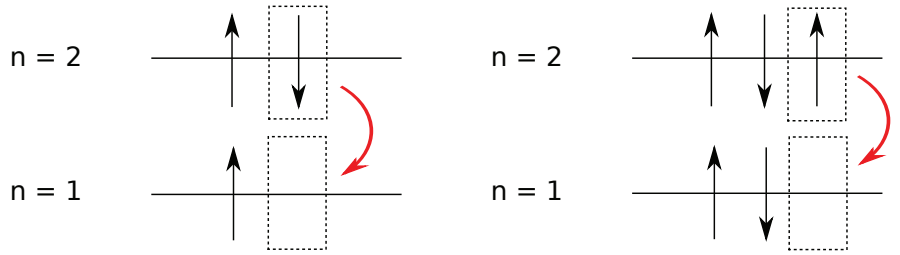

Figure 1: *Normal 2p to 1s transition with an energy around 8 keV for Copper (left) and Pauli-violating 2p to 1s transition with a transition energy around 7,7 keV in Copper (right).*

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.

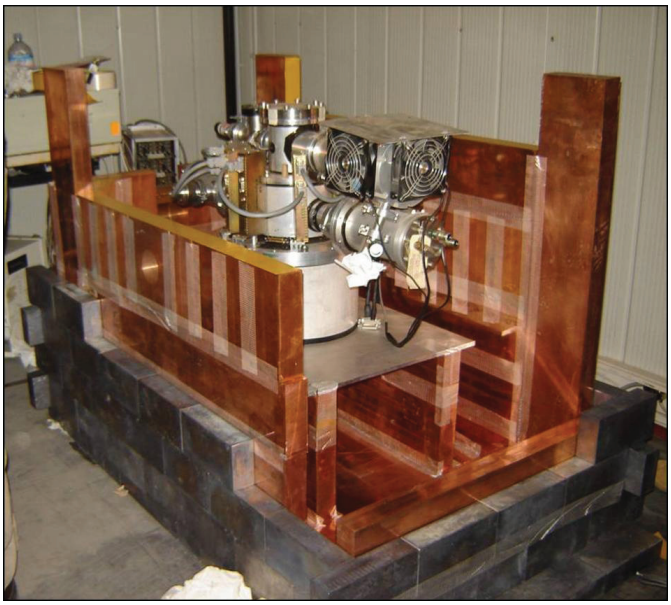

Figure 2: *The VIP setup at the LNGS laboratory during installation.*

In 2018 the VIP2 setup was upgraded with new SDDs and shielding, which was completed in 2019 and is presently in data taking.

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, we built a new setup with a new target, a new cryogenic system and we use new X-ray detectors. As X-ray detectors we use spectroscopic Silicon Drift Detectors (SDDs) which are characterized by better energy resolution than CCDs. The system is providing:

- signal increase with a more compact system with higher acceptance and higher current flow in the new copper strip target;
- background reduction by decreasing the X-ray detector surface and by using a more compact shielding.

The apparatus contains 4 SDD arrays with 2×4 SDDs detectors each (with 8×8 mm^2), mounted close to the Cu target, two on each side (see Figure 3).

In 2019 the lead and cooper shielding were finalized (see Figure 4).

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].

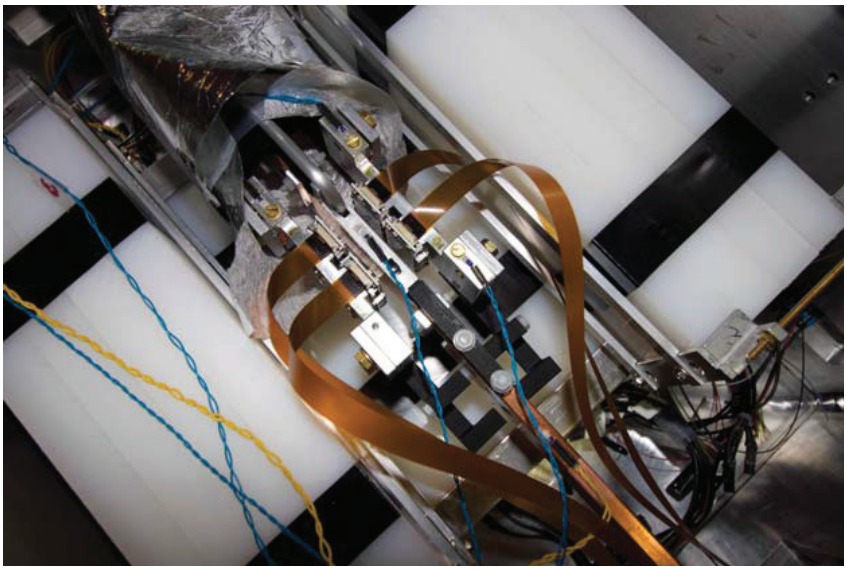

Figure 3: *Picture of the inner part of the VIP-2 setup with the new SDDs installed at LNGS.*

Figure 4: *The VIP-2 shielded setup at LNGS, during installation (upper part here is still to be installed).*

3 VIP-2 Open Systems Activities in 2023, preparation of the future VIP-3 setup and VIP-GATOR collaboration

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 (currently ongoing), alternating periods with and without current circulating in the target. The calibrated and normalized spectra are shown in Figure 5.

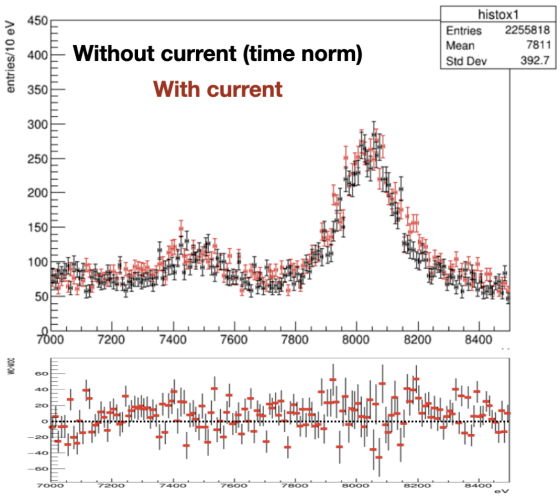

Figure 5: *The calibrated and normalized data are shown, for the two data taking configurations with and without current circulating in the Cu target, in the period September 2023 - January 2024.*

The whole statistics of the VIP-2 acquired data, before the shut down due to the shack renovation (see the previous report), was analyzed (the corresponding paper is under submission) and produced the strongest upper bounds on the PEP violation probability respecting MG, i.e. $\beta^2/2 < 3.1 \cdot 10^{-31}$ in the scattering scheme, $\beta^2/2 < 2.4 \cdot 10^{-43}$ accounting for the electrons random walks. Moreover a review paper was published, reporting the results of a partial statistics data analysis [7].

A refined data analysis was performed of the data collected in current modulation regime, in the period October-December 2020. It consists in a simultaneous spectral and Discrete Fourier Transform Bayesian analysis, which results in a 32% reduction of the limit onto the probability of

PEP violation. A paper presenting these results was accepted for publication in EPJ C.

The realization of the VIP-3 experimental apparatus, aimed to perform a scan of the $\beta^2/2$ as a function of the atomic number, is in an advanced state:

- prototype 1 mm thick SDD arrays were bonded and successfully characterized,
- the design of the PCB support prototype was finalized, prototypes were realized and are currently under testing,
- the design of all the mechanical components, for which the final geometry of the SDD apparatus is necessary, is started (new thermal contact between the cold-finger and SDDs detectors, new target cooling system),
- the SDDs redout electronics is under finalization,
- the new vacuum chamber was realized.

The VIP-GATOR collaboration aims to extend the mapping of the PEP violation probability, for elements characterized by high atomic numbers (e.g. Pb, Au, Pt ...), whose K_α transitions are not measurable even with the improved SDD technology developed within VIP-3. This will be achieved by exploiting a high-performance low-background germanium spectrometer (see also the previous report). A test measurement was performed aimed to check:

- the background conditions with the high radio-purity Pb target installed,
- the low-energy calibration,
- the energy resolution,
- the heat up of the setup under various environments.

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 2023

In collaboration with the theoretical groups of Fudan and Chengdu universities, leaders in the fields of Non Commutative Quantum Gravity (NCQG) models, an analytical expansion of the PEP violation probability was performed in terms of the energies involved in the atomic transitions and the energy scales Λ_k characterizing specific models of space-time non-commutativity. Based on this 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, an accurate measurement of the microphonic noise, in the low radioactivity hosting lab, was performed in collaboration with Ing. Tomassini from LNF (INFN). 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 6. 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 submitted.

5 Collapse Models experimental/phenomenological activity 2023

During 2023, 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) several analyses were finalized:

- A paper was published on dissipative generalizations of the CSL and DP models [11].
- A paper investigating, for the first time, the effect of the correlated electrons-protons emission on the spontaneous emission spectrum, for both white and non-Markovian collapse models was submitted.
- A paper investigating wave function collapse in the context of a stochastic version of the Ricci flow, and obtaining the DP as non-relativistic limit in presence of matter, was submitted [12].

5.1 Events organization in 2023

In 2023 the following events related to the physics of VIP, and, more generally to quantum mechanics, were organized:

- Musing about Quantum Collapse Models: from theory to experiments and back, 8 Jun 2023, Laboratori Nazionali di Frascati (INFN), Italy, https://agenda.infn.it/event/37032/
- COLMO: Quantum Collapse Models investigated with Particle, Nuclear, Atomic and Macro systems, 3-7 July 2023, ECT* (Italy), https://indico.ectstar.eu/event/172/

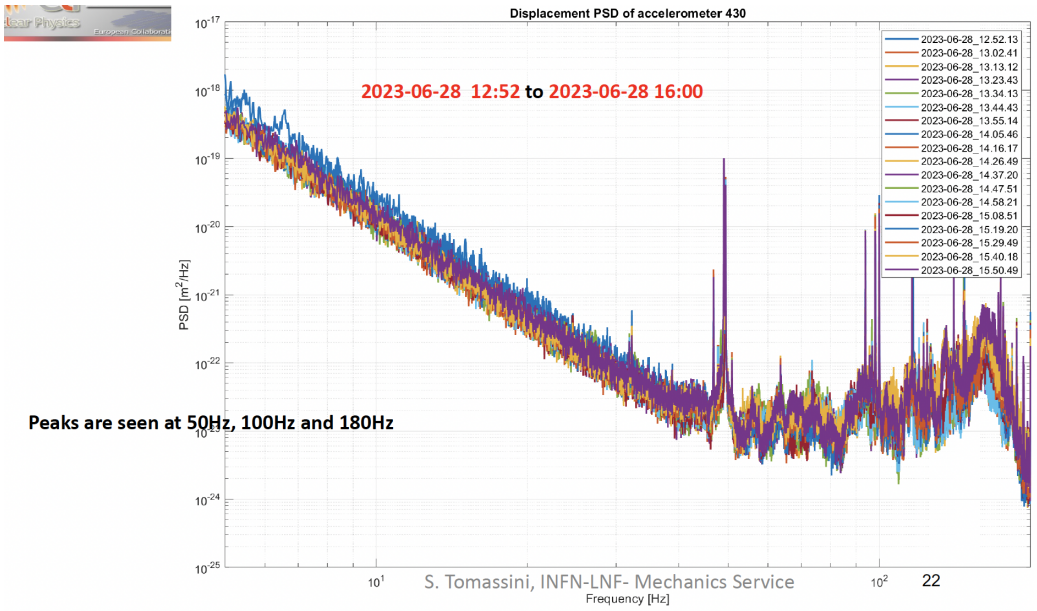

Figure 6: *Displacement power spectral density measured by one of the accelerometers in the laboratory which hosts the BEGe based setup.*

6 Activities in 2024

A schematic description of the activities which will be performed during 2024 is presented:

- we will be in data taking with VIP-2 at LNGS-INFN. The data analyses will be finalized and the corresponding papers will be submitted. In parallel the VIP-3 setup realization will be finalized. VIP-3 will be installed at LNGS end 2024/beginning 2025.
- The final VIP-Gator setup will be realized, and a four months data taking run will be discussed and planned.
- We will prosecute the data taking with the BEGe detector based setup and the data analyses (from both HPGe and BEGe detector based setups), in the contexts of 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.

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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).

7 List of Conference Talks by LNF Authors in 2023

1. C. Curceanu, Quantum cats and neutron stars: From exotic atoms studies to Impossible atoms hunting Colloquium, ANU Canberra, Australia, 3rd March 2023.

2. C. Curceanu, Opportunities to do experiments in an underground laboratory International Workshop "Positronium – from Quantum Physics to Medical Application" 26-28 April 2023, Split (Croazia)

3. C. Curceanu, Experimental tests of collapse models in QM at Gran Sasso and biophotons experiments The Science of Consciousness Conference – Taormina 2023, Italy May 22-27, 2023

4. C. Curceanu, -PET Krakow – positronium for PET and fundamental physics Colloquium, Hvar, John Bell Institute, 15th June 2023

5. C. Curceanu, From the Schroedinger cat To Quantum computers:a quantum symphony Colloqium, Tasmania University, Australia, 15th August 2023

6. C. Curceanu, Testing Quantum Mechanics Underground in the Cosmic Silence: Quantum Collapse models and Pauli Exclusion Principle Violation Colloquium, University of Adelaide CSSM+CDMPP seminar, 23rd August 2023

7. C. Curceanu, Tests of quantum mechanics (in an underground laboratory) Particle & AMO physicists discussing quantum sensors and new physics 2023 MIAPbP, Garching – Germany, 4-8 September 2023

8. C. Curceanu, Testing Quantum Mechanics Underground: Colalpse Models ad the Pauli Exclusion Principle Quantum 2023 - From Foundations of Quantum Mechanics to Quantum Information and Quantum Metrology Sensing 11-15 September 2023, Torino

9. C. Curceanu, Testing Quantum Mechanics Underground in the Cosmic Silence Quantum Collapse models and Pauli Exclusion Principle Symposium on new trends in nuclear and medical physics 18-20 October 2023, Krakow (Poland)

10. C. Curceanu, Testing quantum mechanics in the Cosmic Silence Quantum Collapse and Pauli Exclusion Principle Colloquium, Quantum Seminar - Johannes Gutenberg University Mainz– Germany, 30th November 2023

11. C. Curceanu, Testing quantum mechanics in the Cosmic Silence Quantum Collapse and Pauli Exclusion Principle Colloquium, Sendai Univ, Japan, 18th Decedmber 2023

12. N. Bortolotti, Ongoing work on quantum gravity at VIP, Musing about Quantum Collapse Models: from theory to experiments and back, June 7-8 2023, Laboratori Nazionali di Frascati (INFN), Italy

13. N. Bortolotti, Future perspective in the phenomenological investigation of non-commutative quantum gravity models, Colmo: Quantum collapse models investigated with particle, nuclear, atomic and macro systems, July 3-7 2023, Trento, Italy

14. N. Bortolotti, Probing non-commutative spacetime through the Pauli exclusion principle, Workshop on Noncommutative and Generalized Geometry in String Theory, Gauge Theory and Related Physical Models, September 18-25 2023, Corfù, Grece

15. A. Porcelli, A fine measurement of the Pauli Exclusion Principle with VIP-2, Colmo: Quantum collapse models investigated with particle, nuclear, atomic and macro systems, July 3-7 2023, Trento, Italy.

16. A. Porcelli, Measurements of the Pauli's Exclusion Principle violation with X-Rays detectors: the VIP group, High Precision X-Ray Measurements 2023 (LNF, Frascati, Italy), June 19-23 2023.

17. A. Porcelli, Measurements of the Pauli's Exclusion Principle with VIP group's experiments, Musing about Quantum Collapse Models: from theory to experiments and back, June 7-8 2023, Laboratori Nazionali di Frascati (INFN), Italy.

18. A. Porcelli, Measurement of Pauli Exclusion Principle Violation with Silicon Drift Detector: VIP-2 experiment, Applications of radiation detection techniques in fundamental physics, food control, medicine and biology, Maj 8-12 2023, Laboratori Nazionali di Frascati (INFN), Italy.

19. F. Napolitano, Testing quantum gravity with Germanium Detectors at LNGS, Colmo: Quantum collapse models investigated with particle, nuclear, atomic and macro systems, July 3-7 2023, Trento, Italy.

20. F. Napolitano, Quantum Gravity with VIP at LNGS, Mini workshop on kaonic atoms: present status and future plans, July 18 2023, Laboratori Nazionali di Frascati INFN, Italy

21. F. Napolitano, Testing quantum gravity with Germanium Detectors at LNGS, Applications of radiation detection techniques in fundamental physics, food control, medicine and biology, Maj 8-12 2023, Laboratori Nazionali di Frascati (INFN), Italy.

22. K. Piscicchia, Improved sensitivity X-ray surveys of spontaneous wave function collapse, Colmo: Quantum collapse models investigated with particle, nuclear, atomic and macro systems, July 3-7 2023, ECT*, Trento, Italy.

23. K. Piscicchia, An X-ray survey of wave function collapse signal, High Precision X-Ray Measurements 2023 (LNF, Frascati, Italy), June 19-23 2023.

24. K. Piscicchia, Wave function collapse under test in the cosmic silence, Applications of radiation detection techniques in fundamental physics, food control, medicine and biology, Maj 8-12 2023, Laboratori Nazionali di Frascati (INFN), Italy.

25. K. Piscicchia, Spontaneous radiation as a test of w.f. collapse, future perspectives, Musing about Quantum Collapse Models: from theory to experiments and back, June 7-8 2023, Laboratori Nazionali di Frascati (INFN), Italy.

8 Publications in 2023

1. K. Piscicchia et al., Phys. Rev. D 107, 026002 (2023)
2. F. Napolitano et al., Symmetry 2023, 15(2), 480
3. G. Di Bartolomeo et al., Phys. Rev. A 108, 012202 (2023)
4. P. Moskal et al., Nature Commun. 15 (2024) 1, 78
5. M. Miliucci et al., Appl.Radiat.Isot. 197 (2023) 110822
6. K. Piscicchia et al., Universe 2023, 9(7), 321
7. R. Y. Shopa et al., IEEE Transactions on Radiation and Plasma Medical Sciences, vol. 7, no. 5, pp. 509-520, May 2023,
8. S. Sharma et al., 2023 JINST 18 C02027
9. M. Benfatto et al., Entropy 2023, 25(10), 1431
10. P. Konieczka et al., Mathematical Biosciences and Engineering 2023, Volume 20, Issue 8: 14938-14958
11. S. Sharma et al., EJNMMI Phys 10, 28 (2023)
12. F. Napolitano et al., Meas. Sci. Technol. 35 (2024) 025501
13. K. Piscicchia et al., Entropy 2023, 25(2), 295
14. R. Kaltenbaek et al., Quantum Sci.Technol. 8 (2023) 1, 014006

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2. Curceanu C, Hiesmayer B C and Piscicchia K 2015 Journal of Advanced Physics **4** 1.
3. S. Donadi et al., Eur. Phys. J. C (2021) 81: 773
4. K. Piscicchia et el., Entropy 2023, 25(2), 295
5. E. Milotti et al., Entropy 2018, 20(7), 515
6. E. Milotti et al., Symmetry 2021, 13(1), 6
7. F. Napolitano et al., Symmetry 2023, 15(2), 480
8. S. R. Elliott et al., Found.Phys. 42 (2012)
9. K. Piscicchia et al., Phys. Rev. D 107, 026002 (2023)
10. K. Piscicchia et al., Universe 2023, 9(7), 321
11. G. Di Bartolomeo et al., Phys. Rev. A 108 (2023), 012202
12. M. Lulli, A. Marciano, K. Piscicchia, Stochastic Ricci Flow dynamics of the gravitationally induced wave-function collapse, arXiv:2307.10136 [gr-qc]