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. 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 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 2p $\rightarrow$ 1s transition would differ from the normal 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.

VIP-2 *Open Systems* due to the peculiarity to introduce new fermions (current) in a pre-existing system of identical fermions, is establishing 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, without current. The VIP-2 *Closed Systems* experimental setups are based on extreme radio-purity targets and high purity Germanium detectors. Our goal is to improve the current limits on the new-physics emergence scale, in

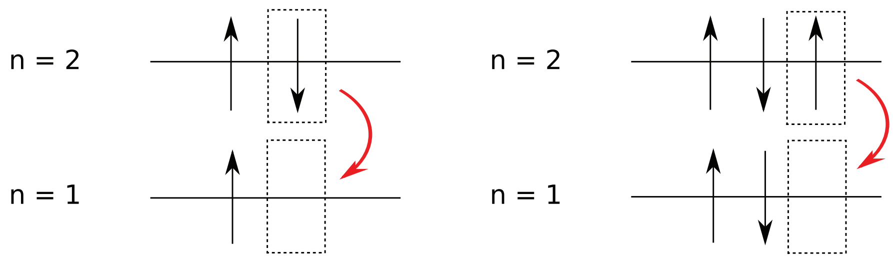

Figure 1: *Normal 2p to 1s transition with an energy around 8 keV for Copper (left) and Pauli-violating 2p to 1s transition with a transition energy around 7,7 keV in Copper (right).*

a regime which is not accessible to current accelerator experiments, thus providing fundamental down-top constraints to the models.

The VIP group has extended its scientific program to the study of other items of the fundamental physics, such as models of 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 2021 report activity 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]. New studies are presently ongoing aimed to challenge generalized versions of the models.

2 The VIP and VIP-2 Open Systems setups

The first VIP setup was realized in 2005, starting from the DEAR setup, reutilizing the CCD (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 probability for 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, and with which we will gain a factor about 100 in the limit on the probability of PEP violation in the coming years.

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

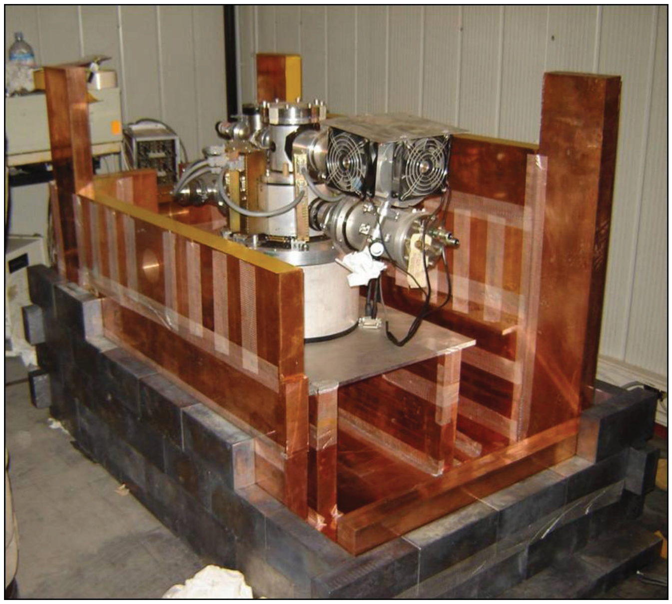

Figure 2: *The VIP setup at the LNGS laboratory during installation.*

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

In order to achieve a signal/background increase which will allow 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 (active veto system and passive).

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, contemporary 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.

3 VIP-2 Open Systems Activities in 2022 and preparation of the future VIP-3 setup

Taking advantage of the data taking interruption, necessary in order to allow the LNGS staff to perform a complex renovation of the shack (reassignment of the spaces, VIP got more space at the first floor), the setup was dismounted and transported to LNF, where an accurate maintenance of the whole apparatus was performed (chamber regeneration, maintenance of inner shielding cooling

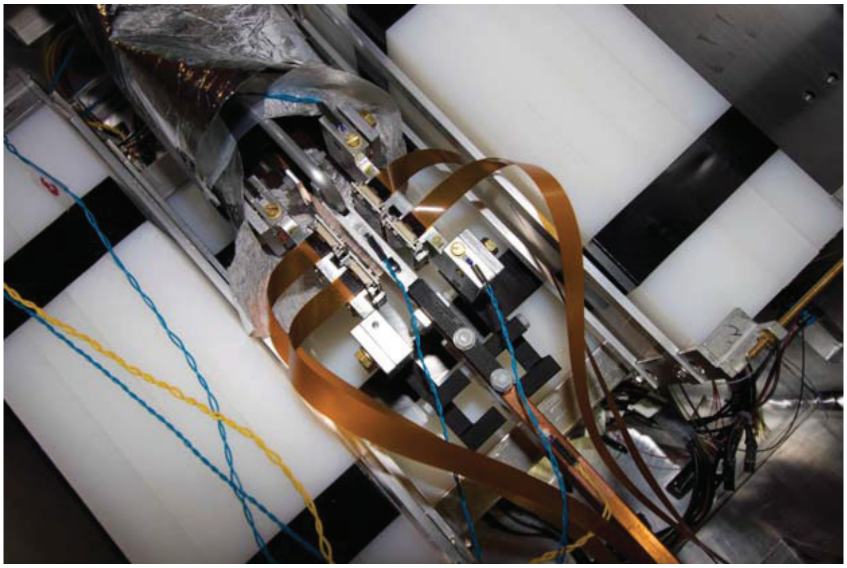

Figure 3: *TA picture of the inner part of the VIP-2 setup with the new SDDs installed at LNGS.*

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

system, revision and cleaning of the pumps, under-vacuum washing of the inner components, maintenance of the SDDs electronics and system, rebuilding of the copper target which was ruined). The setup was reassembled and transported to LNGS in July, after completion of the operations by the LNGS staff in October the data network system was updated, hence the acquisition was restarted (December 2022 - presently ongoing).

The analyses of the data collected without or with partial shielding (2018-May2019), performed by means of the dedicated Bayesian model and validated by means of frequentist CLs exclusion method, exploiting Neyman construction for a robust evaluation of the CLs, were published [4, 5]. Also the analyses of the data (December 2019-May 2020) were completed (upper limits on the PEP violation probability $\beta^2/2 < 8.6 \cdot 10^{-31}$ in the scattering scheme, $\beta^2/2 < 6.8 \cdot 10^{-43}$ accounting for the electrons random walks) and a paper was published [6]. The analyses of the whole data set are under finalization and a paper is under preparation.

The data collected in current modulation regime in the period October-December 2020 were calibrated based on the refined SDD energy calibration procedure. The power spectral density analysis and comparison with signal injection Monte Carlo spectra, to test the sensitivity of the acquired spectra, was performed. The analysis for the extraction of the $\beta^2/2$ upper limit is ongoing.

The activity for 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 ongoing: production of the 1mm thick SDDs in collaboration with FBK Trento was completed, cutting and bonding phases are presently ongoing. The activity proceeded with: design of the new board for the SDD arrays, design of the new vacuum chamber, design of the new cold finger-SDDs thermal contact, design of the new target cooling system. The various components of the setup are presently under development. A paper concerning the VIP-3 activity was published [7].

During 2022 an intense collaboration started with the GATOR facility at LNGS (group ETH Zurich lead by Prof. Laura Baudis), aimed to perform a measurement of $\beta^2/2$ for Pb in opened systems environment. The strong scientific motivation for this measurement consists in the possibility to map the $\beta^2/2$ at very high Z, not accessible with SDD technology (the K_α PEP violating complex in Pb starts at energies as high as about 72 keV, where the efficiency of SDD detectors is too low), with a high-performance low-background germanium spectrometer. Monte Carlo simulations were performed of the resolution, optimized target geometry in terms of detection efficiency and power dissipation. An exploratory measurement was designed, to be performed within 2023, aimed to evaluate the background and to optimize the low-energy calibration.

4 VIP-2 Closed Systems Activities in 2022

Regular meetings with theoretical groups (Fudan and Chengdu universities) leading in the fields of Non Commutative Quantum Gravity (NCQG) models led to:

- the development of a phenomenological model based on the calculated PEP violating atomic transition amplitudes for the Non-Commutative Quantum Gravity models,
- analyses of the data set collected with a High Purity Germanium detector and a high radio-purity Roman lead target. The best limit was obtained on the NCQG θ-Poincaré model, and two papers were published in PRL and PRD [8, 9].

A new collaboration started with Prof. Nick Mavromatos (King's College London) for the study of the VIP results in the context of the CPT deformation induced PEP violation.

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 activity was performed:

- during 2021 the DAQ system realization was completed and the setup was mounted at LNGS (signals from preamplifier are directly fed in the 50 ohm impedance input of the CAEN FADC Mod DT5743 to preserve the signal integrity. The 12bit resolution and 3.2Gs/s sampling rate allows to successfully reconstruct the shape of the incoming signals). A run of three months data taking was performed in the period July-September 2021, for the study of the system spectroscopic response.
- During 2022 the dedicated pulse shape discrimination algorithm, amplitude and shape based, was realized. The events selection and calibration of the acquired spectra was performed, and analyses of the lower energy threshold and resolution were performed. We are also working on an application based on deep convolutional neural network which can be used to discriminate single-site events from multi-site events and noise.
- The analysis of the data acquired in 2021 revealed an intrinsic lower energy threshold of about 20 keV, due to electronic noise at low-voltages and an intrinsic noise of the digitizer at 4 mV. With the aim to lower the energy threshold to 6-7 keV (necessary to measure eventual signal of PEP violating K_α transitions in Ge) an upgraded setup was realized: Flash-ADC-Computer USB connection replaced with optical fibre interface, to reduce electronic noise at low voltages, a wide band low noise amplifier was introduced in the acquisition chain in order to obtain a gain 10 in tension. A new data taking started in Feb 2022 (presently ongoing), which already demonstrated the capability of the new setup to lower the energy threshold to 6/7 keV. The block diagram and an image of the setup are shown in Figure 5.

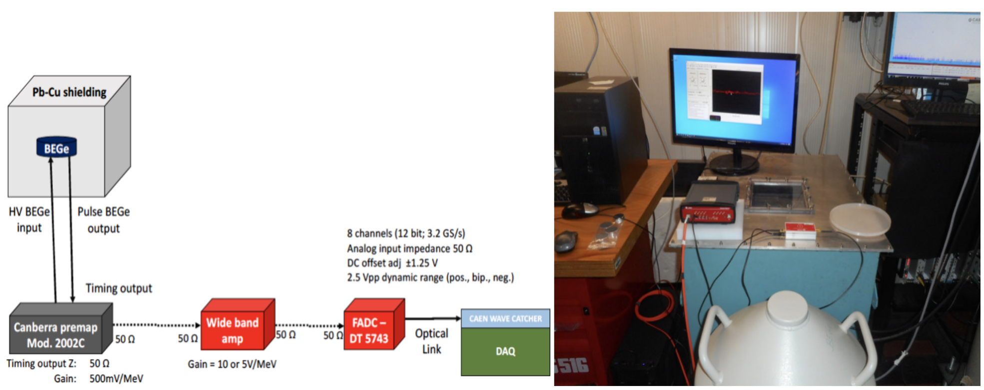

Figure 5: *Block diagram of the BEGe based system presently in data taking (left). Picture of the setup on the right.*

5 Collapse Models experimental/phenomenological activity 2022

During 2022 the analyses of the data collected with a dedicated High Purity Germanium detector based setup (HPGe), and a constant collaboration with leading theoretical groups in this field

(Roger Penrose Univ of Oxford, Steven Adler Princeton Univ., Lajos Diosi Eotvos Univ. and Angelo Bassi Trieste Univ.), led to the publication/submission/finalization of several papers:

- the analysis of the data collected with HPGe detector (2014-2015 runs) lead to the first separate determination of the probability density functions of the strength and correlation length of the CSL model. [10]
- One paper on the consequences of our findings concerning the Diosi-Penrose model [1] on the Orchestrated objective reduction model of Hameroff and Penrose was published [11], which is having a strong media impact.
- Dissipative generalizations of the collapse models were developed [12].
- The spontaneous emission rate in case of correlated electrons-nucleons emission, for both white and non-Markovian collapse models was calculated [13].

5.1 Events organization in 2022

In 2022 the following events related to the physics of VIP, and, more generally to quantum mechanics, were organized:

- The Hitchhiker's Advanced Guide to Qauntum Collapse Models and their impact in science, philosophy, technology and biology, 31 Oct - 4 Nov 2022, LNF (INFN), Italy, https://agenda.infn.it/event/32081//
- Nuclear and Atomic Transitions as Laboratories for High Precision Tests of Quantum Gravity inspired Models, 19-23 Sept. 2022, ECT*, https://indico.ectstar.eu/event/147/registrations/29

6 Activities in 2023

During 2023 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 2023/beginning 2024.

A test measurement will be performed by VIP in collaboration with the GATOR facility.

We will prosecute data analyses (from both HPGe and BEGe detector based setups) in the contexts of Non Commutative Quantum Gravity 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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7 List of Conference Talks by LNF Authors in 2022

1. C. Curceanu, Testing Quantum Mechanics Underground In the Cosmic Silence, 24th Australian Institute of Physics Congress, Adelaide, Australia.
2. C. Curceanu, Testing Quantum Mechanics Underground Sneaking a look at God's cards, Lisbon Philosophy of Physics Seminars 2022-2023, Lisbon, Portugal.
3. C. Curceanu, Fundamental symmetries Nuclear Physics Mid Term Plan in Italy - LNGS Session, LNGS, Italy.
4. C. Curceanu, Experimental studies of collapse models as basis of consciousness and the photons emission by germinating plants, Nuclear and Atomic transitions as laboratories for high precision tests of Quantum Gravity inspired models, ECT* Trento, Italy.
5. C. Curceanu, Blues in the Cosmic Silence: testing Quantum Mechanics Underground Strike another match, go start anew, Laws of Nature Conference Munich, Germany.
6. C. Curceanu, Experimental tests of QM from collapse models to the Pauli exclusion principle, IAP 2022 Conference, Paris, France
7. C. Curceanu, Testing Quantum Mechanics Underground: Sneaking a look at God's cards Mind and Agency in the Foundations of Quantum Physics, Chapman University, AF211.
8. C. Curceanu, Testing Quantum Mechanics Underground, Colloquium at Rurgers University, USA.
9. C. Curceanu, Underground tests of Quantum Mechanics - Collapse models and Pauli Exclusion Principle INFN 2022 Conference, LNGS, Italy.
10. K. Dulski, The decay rate of o-Ps with the J-PET detector, The Hitchhiker's Advanced Guide to Quantum Collapse Models and their impact in science, philosophy, technology and biology, Frascati, Italy.
11. S. Manti, Cascade models for atomic transitions, The Hitchhiker's Advanced Guide to Quantum Collapse Models and their impact in science, philosophy, technology and biology, Frascati, Italy.
12. F. Napolitano, Testing the Pauli Exclusion Principle and Collapse Models in underground experiments, DISCRETE2022, Baden-Baden, Germany.
13. F. Napolitano, Underground Tests of Quantum Collapse at Gran Sasso, The Hitchhiker's Advanced Guide to Quantum Collapse Models and their impact in science, philosophy, technology and biology, Frascati, Italy.
14. F. Napolitano, Quantum collapse Models and their experimental tests, Nuclear Physics Mid Term Plan in Italy, LNGS, Italy.
15. F. Napolitano, Pauli Exclusion Principle violations and quantum gravity with the VIP-2 underground experiment, ECT* Nuclear and Atomic transitions as laboratories for high precision tests of Quantum Gravity inspired models, Trento, Italy.
16. F. Napolitano, Testing the Pauli Exclusion Principle with the VIP-2 Experiment and Beyond" SIF national congress, Milano, Italy.

17. F. Napolitano, Testing the Pauli Exclusion Principle with the VIP-2 Experiment and Beyond, XI international Conference on New Frontiers in Physics, ICNFP (online)
18. F. Napolitano, Experimental tests of Quantum Mechanics: from collapse models to the Pauli Exclusion Principle, Quantum Information and Probability: from Foundations to Engineering (QIP22) 14 Jun 2022 - 17 Jun 2022, Växjö, Sweden.
19. K. Piscicchia, High Sensitivity Tests of Quantum Gravity induced Spin Statistics Deformation, The Hitchhiker's Advanced Guide to Qauntum Collapse Models, LNF (INFN), Italy.
20. K. Piscicchia, Testing Quantum foundations in the cosmic silence, 4th Jagellonian Symposium on Advances in Particle Physics and Medicine, Krakow, Poland.
21. K. Piscicchia, Symmetries investigation through PEP high sensitivity tests, Nuclear Physics Mid Term Plan in Italy - LNGS session, LNGS (L'Aquila), Italy.
22. K. Piscicchia, Wave function collapse models tests in the cosmic silence, Nuclear and Atomic transitions as laboratories for high precision tests of Quantum Gravity inspired models, ECT*, Trento, Italy.
23. K. Piscicchia, Quantized-gravity and "gravitzed"-quantum, testing spin-statistics and quantum collapse in the cosmic silence, IQIS2022,Palermo, Italy.
24. K. Piscicchia, Phenomenology of the spontaneous radiation search, present and future, Fundamental Problems in Quantum Physics 2022, second school on quantum foundations dedicated to Prof. GianCarlo Ghirardi, Trieste, Italy
25. K. Piscicchia, Searching for signal of wave function collapse in the cosmic silence, ICNFP 2022, Kolymbari, Crete, Grece.
26. K. Piscicchia, High sensitivity tests of Quantum Mechanics foundations , ICRM-LLRMT 2022, Laboratori Nazionali del Gran Sasso, Italy.
27. A. Porcelli, Accurate analysis method to detect rare events in VIP-2", Nuclear and Atomic transitions as laboratories for high precision tests of Quantum Gravity inspired models Workshop, ECT*, Trento. Italy.
28. A. Porcelli, Searches for a possible violation of the Pauli Exclusion Principle in the Gran Sasso underground laboratory: the VIP-2 experiment. KSETA 10th year Symposium, Karlsruher Institut für Technologie, Karlsruhe, Germany.
29. A. Porcelli, High sensitivity analysis on Pauli's Exclusion Principle violation with VIP-2, The Hitchhiker's Advanced Guide to Quantum Collapse Models and their impact in science, philosophy, technology and biology, Frascati, Italy.

8 Publications in 2022

1. C. Curceanu *et al*, Snowmass 2021 Topical Report on Synergies in Research at Underground Facilities, e-Print: 2210.03145 [hep-ex].
2. L. De Paolis *et al*, The Pauli Exclusion Principle for electrons tested by VIP-2 at the LNGS laboratories, Nuovo Cim.C 45 (2022) 5, 103.
3. K. Piscicchia *et al*, High Sensitivity Pauli Exclusion Principle Tests by the VIP Experiment: Status and Perspectives, Acta Phys.Polon.A 142 (2022) 3, 361-366

4. K. Piscicchia *et al*, Strongest Atomic Physics Bounds on Noncommutative Quantum Gravity Models, Phys.Rev.Lett. 129 (2022) 13, 131301.
5. L. De Paolis *et al*, Search for a signature of Pauli exclusion principle violation by VIP-2, Phys.Scripta 97 (2022) 8, 084001.
6. F Napolitano *et al*, Testing the Pauli Exclusion Principle with the VIP-2 Experiment, Symmetry 14 (2022) 5, 893.
7. C. Curceanu *et al*, Underground tests of Quantum Mechanics at Gran Sasso, PoS DISCRETE 2020-2021 (2022) 005.
8. P. Moskal, C. Curceanu *et al*, From tests of discrete symmetries to medical imaging with J-PET detector, PoS PANIC2021 (2022) 033.
9. L. De Paolis *et al*, Testing Pauli Exclusion Principle for electrons at the LNGS underground laboratory: The VIP-2 experiment, PoS PANIC2021 (2022) 456.
10. M.Derakhshani, L. Diósi, M. Laubenstein, K. Piscicchia, C. Curceanu, At the crossroad of the search for spontaneous radiation and the Orch OR consciousness theory, Physics of Life Reviews, Volume 42 (2022) 8.
11. C. Curceanu *et al*, Underground Tests of Quantum Mechanics at Gran Sasso, PoS DISCRETE 2020-2021 (2022) 005
12. L. De Paolis et al., Testing Pauli Exclusion Principle for electrons at the LNGS underground laboratory: The VIP-2 experiment, PoS PANIC2021 (2022) 456
13. A. Porcelli et al., Analysis methods used and planned for VIP-2, EPJ Web Conf. 262 (2022) 01022

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4. L. De Paolis et el., Phys.Scripta 97 (2022) 8, 084001
5. L. De Paolis et el., Nuovo Cim.C 45 (2022) 5, 10
6. F. Napolitano et al., Symmetry 14 (2022) 5, 893
7. K. Piscicchia et al., Acta Phys.Polon.A 142 (2022) 3, 361-366
8. K. Piscicchia et al., Phys.Rev.Lett. 129 (2022) 13, 131301
9. K. Piscicchia et al., Phys. Rev. D 107, 026002 (2023)
10. K. Piscicchia et el., Entropy 2023, 25(2), 295
11. M. Derakhshani et al., Physics of Life Reviews, Volume 42, 2022, Pages 8-14)
12. G. Di Bartolomeo, M. Carlesso, K. Piscicchia., C. Curceanu, M. Derakhshani, L. Diosi arXiv:3201.07661[quant-ph]
13. K. Piscicchia, S. Donadi, S. Manti, A. Bassi, C. Curceanu, arXiv:2301.09920 [quant-ph]