VIP

S. Bartalucci, M. Bazzi, M. Benfatto, A. Clozza,
C. Curceanu (Resp. LNF), R. Del Grande (Ass.), C. Guaraldo,
J. Marton (Ric. Str.), M. Miliucci (Dott.), K. Piscicchia (Resp. Naz.) ,
E. Pace, D. Sirghi (Ass.), L. Sperandio (Ric. Str.),

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 25 years, 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, ($P < 1.7 \times 10^{-26}$ 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 (Fig. 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. The rather straightforward analysis consists in the evaluation of the statistical significance of the normalized subtraction of the two spectra in the region of interest (if no signal is seen). A more complex statistical analysis (such as Bayesian) is also being implemented.

In 2020 we have extended the scientific program towards a search of PEP violation predicted by Quantum Gravity inspired models, by using a HPGe detector (no current is necessary in this type of study).

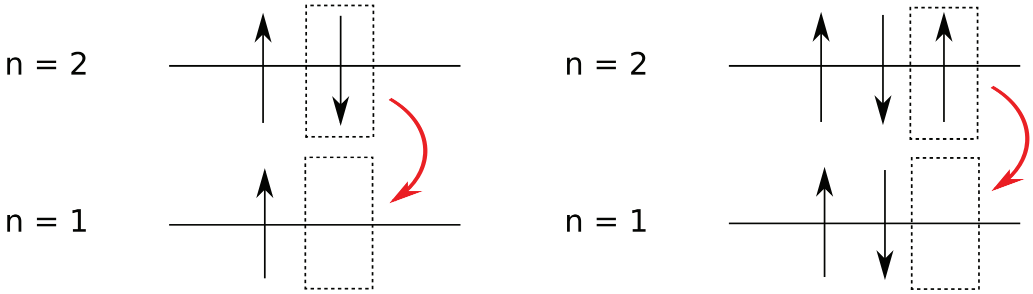

Figure 1: *Normal 2p to 1s transition with an energy around 8 keV for Copper (left) and Pauli-violating 2p to 1s transition with a transition energy around 7,7 keV in Copper (right).*

The experiments are being performed at the LNGS underground Laboratories, where the X-ray background, generated by cosmic rays, is strongly reduced.

The VIP group has extended its scientific program to the study of other items of the fundamental physics, such as discrete symmetries and dynamical collpase models. Encouraging first results were already obtained.

2 The VIP and VIP-2 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 Fig. 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, 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 probability of PEP violation in the coming years (see Table 1).

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

3 Activities in 2020

3.1 VIP-2 - 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 detectors with timing capability and an active veto system. As X-ray detectors we use spectroscopic Silicon Drift Detectors (SDDs) which have an even better energy resolution than CCDs and provide timing capability which allow to use anti-coincidence

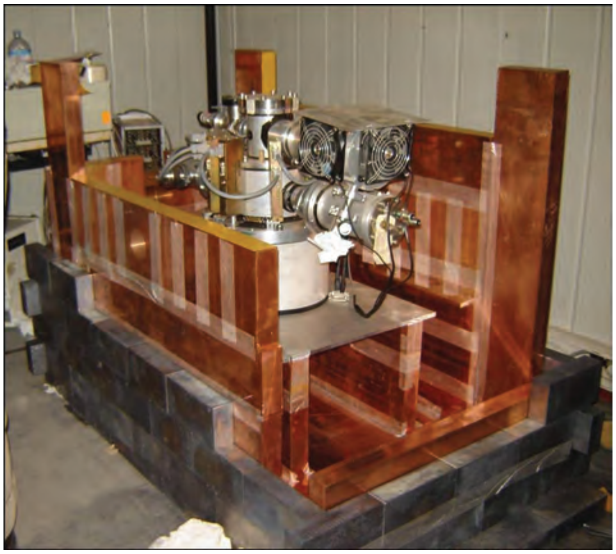

Figure 2: The VIP setup at the LNGS laboratory during installation.

provided by an active shielding.
The VIP-2 system is providing:

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

In the Table 1 the numerical values for the improvements in VIP-2 are given which will lead to an expected overall improvement of a factor about 100.

3.2 Status of VIP-2 in 2020

The VIP-2 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).

In 20202, data with 180 Ampere DC current applied to the copper strip was collected together with the data collected without current, representing the background. The data analysis is ongoing and a paper in preparation.

3.3 VIP-2 data analyses in 2020

During 2020 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 and semi-analytical Monte Carlo methods to simulate the signal of the VIP-2 experiment (see publication list).

By applying these methods a new limit of PEP violation is obtained as:

$$\frac{\beta^2}{2} \leq 5.4 \times 10^{-42}. \tag{1}$$

Table 1: List of expected gain factors of VIP-2 in comparison to VIP (given in brackets).

Changes in VIP-2	value VIP-2(VIP)	expected gain
acceptance	12% (1%)	12
increase current	100A (50A)	2
reduced length	3 cm (8.8 cm)	1/3
total linear factor		8
energy resolution	170 eV(340 eV)	4
reduced active area	6 cm^2(114 cm^2)	-
better shielding and veto		5-10
higher SDD efficiency		1/2
background reduction		200-400
overall gain		**~120**

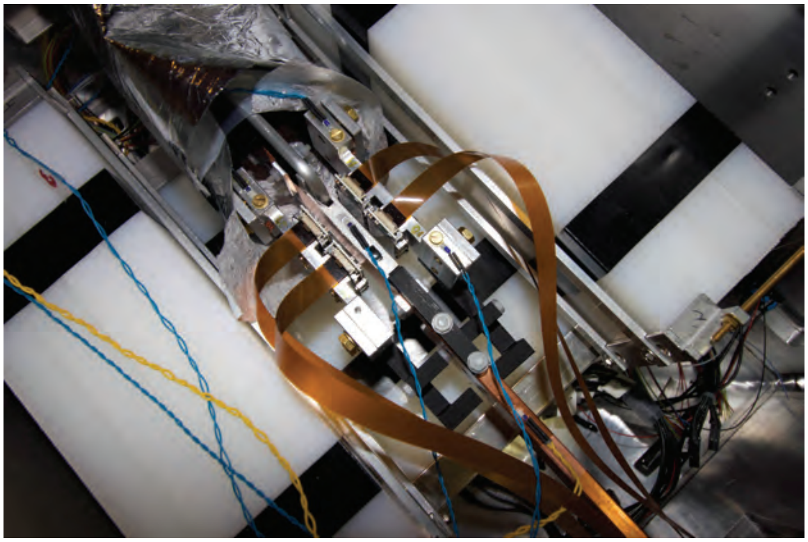

Figure 3: *A picture of the inner part of the VIP-2 setup with the new SDDs installed at LNGS .*

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

published in Entropy 22 (2020), 11, 1195.

Discussions with theoretician about the interpretation of results are ongoing.

4 X-ray measurements for testing the dynamical reduction models

The aim of the Dynamical Reduction Models (DRM) is to solve the so-called "measurement problem" in Quantum Mechanics (QM). The linear and unitary nature of the Shrödinger equation allows, in principle, the superposition of macroscopic states, but such superpositions are not observed in the measurement process, which is intrinsically non-linear and stochastic 1, 2). The measurement problem led to the introduction of the wave packet reduction principle which, nevertheless, does not predict the scale at which the quantum-to-classical transition occurs, nor explains the collapse mechanism.

The work of Ghirardi, Rimini and Weber 3) lead to the development of a consistent DRM known as Quantum Mechanics with Spontaneous Localization (QMSL). According to the QMSL model each particle of a macroscopic system of n distinguishable particles experiences sudden spontaneous localizations, on the position basis, with a mean rate $\lambda = 10^{-16}$ s^{-1}, and a correlation length $a = 10^{-7}$ m. Between two localizations particles evolve according to the Shrödinger dynamics. The model ensures, for the macroscopic object, the decoupling of the interanl and Center of Mass (CM) motions. The interanl motion is not affected by the localization, whereas the CM motion is localized with a rate $\lambda_{macro} = n\,\lambda$.

Subsequently, the theory was developed in the language of the non-linear and stochastic Shrödinger equation 4, 5), where besides the standard quantum Hamiltonian, two other terms induce a diffusion process for the state vector, which causes the collapse of the wave function in space. In its final version 6) the model is known as the mass proportional Continuous Spontaneous Localization (CSL).

The value of the mean collapse rate is presently argument of debate. According to CSL λ should be of the order of 10^{-17} s^{-1}, whereas a much stronger value $10^{-8\pm2}$ s^{-1} was proposed by S. L. Adler 8) based on arguments related to the latent image formation and the perception of the eye.

DRM posses the unique characteristic to be experimentally testable, by measuring the (small) predicted deviations with respect to the standard quantum mechanics. The conventional approach is to generate spatial superpositions of mesoscopic systems and examine the loss of interference, while environmental noises are, as much as possible, under control. The present day technology, however, does not allow to set stringent limits on λ by applying this method. The most promising testing ground, instead, is represented by the search for the spontaneous radiation emitted by charged particles when interacting with the collapsing stochastic field 7). A measurement of the emitted radiation rate thus enables to set a limit on the λ parameter of the models.

The radiation spectrum spontaneously emitted by a free electron, as a consequence of the interaction with the stochastic field, was calculated by Q. Fu 7) in the framework of the non-relativistic CSL model, and it is given by:

$$\frac{d\Gamma(E)}{dE} = \frac{e^2\lambda}{4\pi^2 a^2 m^2 E} \tag{2}$$

in eq. (2) m represents the electron mass and E is the energy of the emitted photon. In the mass proportional CSL model the stochastic field is assumed to be coupled to the particle mass density, then the rate is to be multiplied by the factor $(m/m_N)^2$, with m_N the nucleon mass. Using the measured radiation appearing in an isolated slab of Germanium 9) corresponding to an energy of 11 KeV, and employing the predicted rate eqn. (2), Fu obtained the following upper limit for λ (non-mass poportional model):

$$\lambda < 0.55 \cdot 10^{-16} s^{-1}. \tag{3}$$

In eq. (3) the QMSL value for a ($a = 10^{-7}$ m) is assumed and the four valence electrons were considered to contribute to the measured X-ray emission, since the binding energy is $\sim$ 10 eV in this case, and they can be considered as *quasi-free*. Recent re-analyses of Fu's work 8, 10) corrected the limit to $\lambda < 2 \cdot 10^{-16} s^{-1}$.

We already improved the limit on the collapse rate 11) by analysing a set of data collected at LNGS with Ge detectors and an ultra-pure lead target.

Recently, we consider a particular collapse model, related to gravity, the Diosi-Penrose collapse model. We analysed our data within this framework, and obtained the best limit ever on the R_0 parameter characterizing the model. Our result was recently published in Nature Physics 17 (204) 74-78, and was raising lot of interest from scientific community and general public.

By using a similar method, we are considering the idea to perform other dedicated experiments at LNGS which will allow for 1 - 2 orders of magnitude further improvement on the collapse models parameters. Related with this, in 2020 Dr. C. Curceanu won an FQXi grant.

4.1 Workshop organization

In 2020 the following event related to the physics of VIP, and, more generally, to quantum mechanics, was organized:

Is Quantum theory exact? Exploring Quantum Boundaries, LNF-INFN, online, 10-11 December 2020.

5 Activities in 2021

In 2021 we will be in data taking with VIP-2 at LNGS-INFN. The previous data analysis will be finalized and published. We shall also perform measurements with closed systems (no current) for testing Quantum Gravity models. We will, as well, continue the studies on fundamental physics, in particular on the collapse model by measurements of X rays spontaneously emitted in the continuous spontaneous localization (CSL) and gravity-related collapse models.

Acknowledgements

The VIP-2 Collaboration wishes to thank all the LNGS laboratory staff for the precious help and assistance during all phases of preparation, installation and data taking.

The support from the EU COST Action CA 15220 and from HP220 FET TEQ (grant nr. 766900) is gratefully acknowledged.

Furthermore, we acknowledge the support from the Foundational Questions Institute, FOXi and from the John Templeton Foundation (ID 581589).

6 Publications in 2020

1. K. Piscicchia *et al*, High Sensitivity Quantum Mechanics Tests in the Cosmic Silence, Acta Phys. Polon. Supp. **14** (2021) 151.
2. E. Milotti *et al*, Semi-Analytical Monte Carlo Method to Simulate the Signal of the VIP-2 Experiment, Symmetry **13** (2020) 1, 6.
3. K. Piscicchia *et al*, VIP-2 - High-Sensitivity Tests on the Pauli Exclusion Principle for Electrons, Entropy **22** (2020) 11, 1195.
4. K. Piscicchia *et al*, High precision test of the Pauli Exclusion Principle for electrons, J. Phys. Conf. Ser. **1586** (2020) 1, 012016.
5. S. Donadi *et al*, Underground test of gravity-related wave function collapse, Nature Phys. **17** (2021) 1, 78.
6. P. Moskal *et al*, Synchronization and Calibration of the 24-Modules J-PET Prototype With 300-mm Axial Field of View, IEEE Trans.Instrum.Measur. **70** (2020) 10.
7. K. Dulski *et al*, First exclusive measurement of ortho-positronium with the J-PET tomograph, e-Print: 2006.07467 [physics.ins-det].
8. K. Piscicchia *et al*, Search for a remnant violation of the Pauli exclusion principle in a Roman lead target, Eur. Phys. J. C **80** (2020) 6, 508.
9. L. De Paolis *et al*, The key role of the Silicon Drift Detectors in testing the Pauli Exclusion Principle for electrons: the VIP-2 experiment, J. Phys. Conf. Ser. **1548** (2020) 1, 012033.
10. N. G. Sharma *et al*, Hit-time and hit-position reconstruction in strips of plastic scintillators using multi-threshold readouts, e-Print: 2004.12742 [physics.ins-det]
11. J. Marton *et al*, VIP-2 - Testing spin-statistics for electrons with high sensitivity, J. Phys. Conf. Ser. **1468** (2020) 1, 012230.
12. E. Milotti *et al*, New Concepts in Tests of the Pauli Exclusion Principle in Bulk Matter, Acta Phys .Polon.B **51** (2020) 96.

13. K. Piscicchia *et al*, Testing the Pauli Exclusion Principle in the Cosmic Silence, Acta Phys. Polon. B **51** (2020) 102.
14. J. Marton *et al*, VIP2 at Gran Sasso - Test of the validity of the spin statistics theorem for electrons with X-ray spectroscopy, J. Phys. Conf. Ser. **1342** (2020) 1, 012087.

References

1. Von Neumann J 1932 Mathematische Grundlagen der Quantummechanik (Springer-Verlag). English translation 1955: Mathematical Foundations of Quantum Mechanics (Princeton University Press)
2. Bassi A and Ghirardi G C 2003 *Phys. Rep.* **379** 257
3. Ghirardi G C, Rimini A and Weber T 1986 *Phys. Rev. D* **34** 47
4. Pearle P 1989 *Phys. Rev. A* **39** 2277
5. Ghirardi G C, Pearle P and Rimini A 1990 *Phys. Rev. A* **42** 78
6. Pearle P and Squires E 1994 *Phys. Rev. Lett.* **73** 1
7. Fu Q 1997 *Phys. Rev. A* **56** 1806
8. Adler S L 2007 *Journal of Physics A* **40** 2935
9. Miley H S *et al* 1990 *Phys. Rev. Lett.* **65** 3092
10. Mullin J and Pearle P 2014 *Phys. Rev. A* **90** 052119
11. Curceanu C, Hiesmayer B C and Piscicchia K 2015 *Journal of Advanced Physics* **4** 1.
12. Donadi S, *et al*, 2021 *Nature Phys.* **17** 1, 78.