VIP

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1 The VIP scientific case and the experimental method

Within VIP an experimental test on the Pauli Exclusion Principle 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 20 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 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 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 (Boyesian) is also being implemented.

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

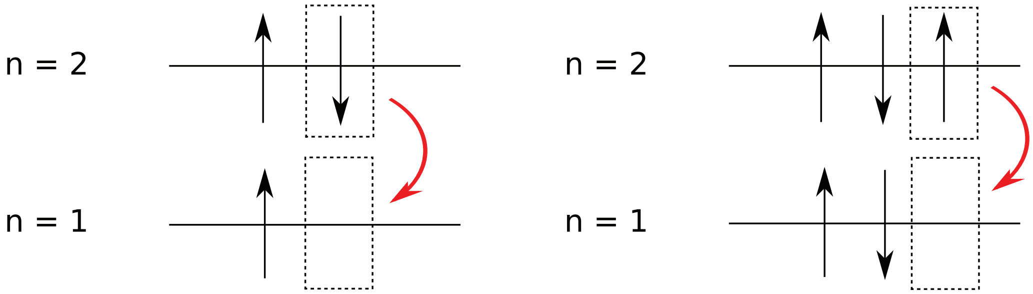


Figure 1: *Normal 2p to 1s transition with an energy around 8 keV for Copper (left) and Pauli-violating 2p to 1s transition with a transition energy around 7,7 keV in Copper (right).*

The VIP group is considering also the extension of its scientific program to the study of other items of the fundamental physics, such as discrete symmetries and collpase models. Encouraging preliminary results were obtained.

2 The VIP and VIP2 apparata

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.

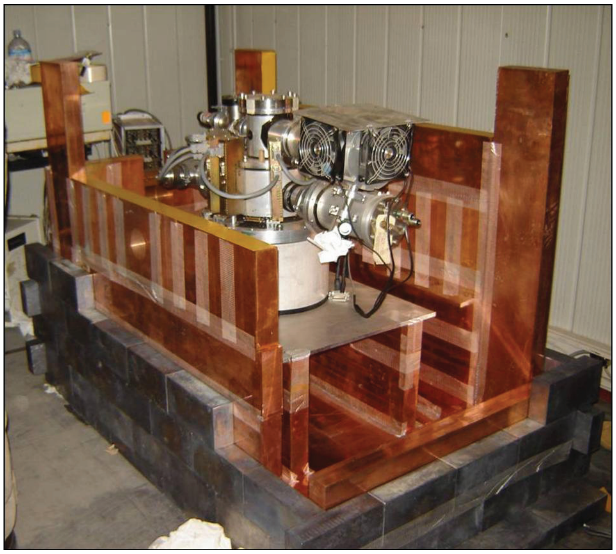


Figure 2: The VIP setup at the LNGS laboratory during installation.

Table 1: List of expected gain factors of VIP2 in comparison to VIP (given in brackets).

Changes in VIP2	value VIP2(VIP)	expected gain
acceptance	12%	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)	20
better shielding and veto		5-10
higher SDD efficiency		1/2
background reduction		200-400
overall gain		**∼120**

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, VIP2, which 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).

3 Activities in 2017

3.1 VIP2 - 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 provided by an active shielding.
The VIP2 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, more compact shielding (active veto system and passive), nitrogen filled box for radon radiation reduction.

In the Table 1 the numerical values for the improvements in VIP2 are given which will lead to an expected overall improvement of a factor about 100.

3.2 Status of VIP2 in 2017

In the VIP2 apparatus six SDDs units, with a total active area of 6 cm^2 each are mounted close to the Cu target. Moreover, an active shielding system (veto) was implemented, to reduce the background in the energy region of the forbidden transition. These systems will play an important role to improve the limit for the violation of the PEP by two orders of magnitude with the new data which are presently comming by running the VIP2 experiment at LNGS.

In November 2015, the VIP2 setup was installed at Gran Sasso. In the years 2016 and 2017, data with the VIP2 detector system at the LNGS without shielding were taken. In Figure 3 the VIP2 setup as installed at LNGS is shown.

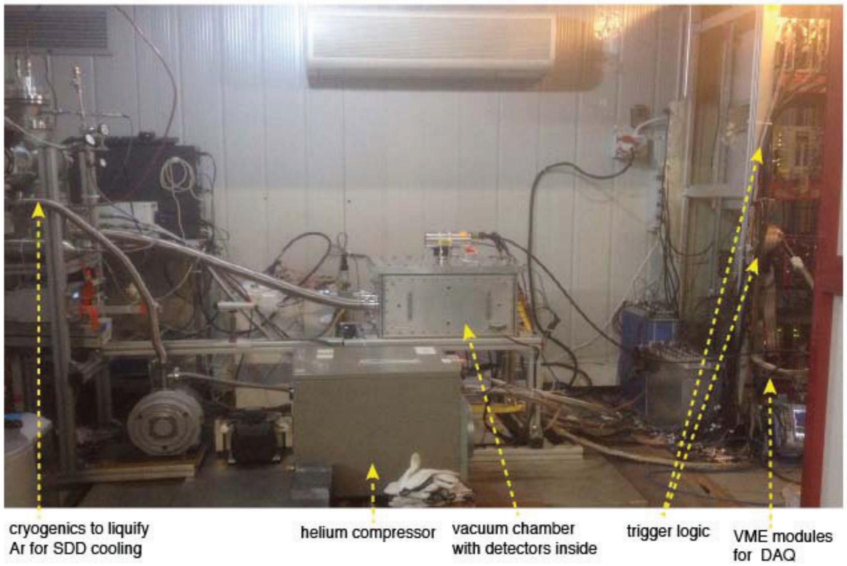


Figure 3: *A picture of the VIP-2 setup installed at LNGS .*

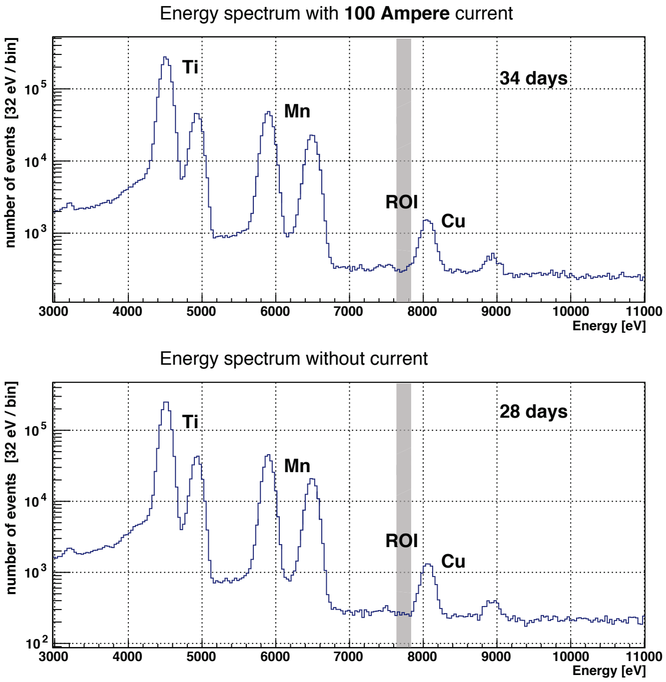
Data with 100 Ampere DC current applied to the copper strip was collected together with the data collected without current.

Preliminary data analyses "a la VIP": two types of preliminary data referring to the first period of data taking (data from 2016) were performed: one "a la VIP", i.e. using exactly the same procedure as the one used in VIP (subtracted spectra: with and without current). The result which was obtained was published in the review: Entropy, 2017, 19, p. 300. The obtained calibrated energy spectra for all 6 SDDs are shown in Fig. 4 and their analysis allowed to extract a limit on the probability for PEP violation as:

$$\frac{\beta^2}{2} \leq \frac{3 \times 66}{4.7 \times 10^{30}} = 4.2 \times 10^{-29}. \tag{1}$$

which is slightly better (10% than the one for VIP. To be underlined that the limit was obtained after two months of data taking, while the VIP one corresponds to 4 years of data taking.

Preliminary data analyses with a new method: the same set of data analysed by using a different method, i.e. a simultaneous fit of the "signal" and background spectra, in order to use all the information available for the background shape from the data. The obtained spectra


Energy spectrum with **100 Ampere** current

Energy spectrum without current

Figure 4: *The energy spectra from all the SDDs, for data with and without applied DC current to the copper strip, taken during the physics run in late 2016 at the LNGS.*

are shown in Fig 5, together with the simultaneous fitting functions, from where a limit of the probability of PEP violation was extracted to be:

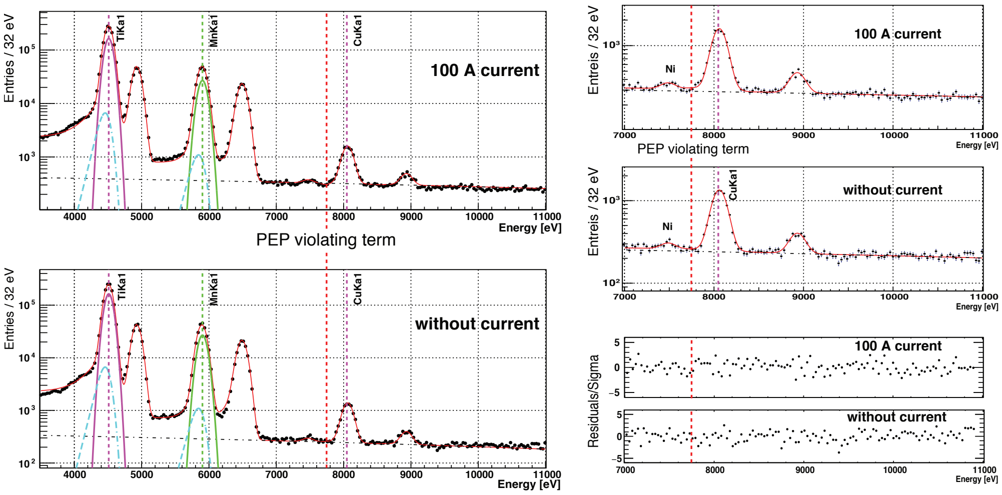
$$\frac{\beta^2}{2} \leq \frac{3 \times 67}{8.1 \times 10^{30}} = 3.2 \times 10^{-29}. \tag{2}$$

A paper is presently in preparation describing the new analysis and the obtained results.

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



(a)

(b)

Figure 5: *A global chi-square function was used to fit simultaneously the spectra with and without 100 A current applied to the copper conductor. The energy position for the expected PEP violating events is about 300 eV below the normal copper* $K_{\alpha 1}$ *transition. The Gaussian function and the tail part of the* $K_{\alpha 1}$ *components and the continuous background from the fit result are also plotted. (a) : the fit to the wide energy range from 3:5 keV to 11 keV; (b) : the fit and its residual for the 7 keV to 11 keV range where there is no background coming from the calibration source. See the main text for detail*

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 $10^{-8\pm 2}$ 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:

$$\frac{d\Gamma(E)}{dE} = \frac{e^2\lambda}{4\pi^2 a^2 m^2 E} \tag{3}$$

in eq. (3) 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. (3), Fu obtained the following upper limit for λ (non-mass poportional model):

$$\lambda < 0.55 \cdot 10^{-16} s^{-1}. \tag{4}$$

In eq. (4) 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 in Eq. 6 to $\lambda < 2 \cdot 10^{-16} s^{-1}$.

We improved the limit on the collapse rate 11) by analysing the data collected by the IGEX (International Germanium EXperiment) experiment 12). IGEX is a low-background experiment based on low-activity Germanium detectors dedicated to the $\beta\beta 0\nu$ decay research. We performed a fit of the published X-ray emission spectrum 13), which refers to an 80 kg day exposure, in the energy range $\Delta E = 4.5 \div 48.5$ KeV $\ll m$. The energy interval is compatible with the non-relativistic assumption of the model (Eq. (3)).

A Bayesian model was adopted to calculate the χ^2 variable minimized to fit the X ray spectrum, assuming the predicted (Eq. (3)) energy dependence:

$$\frac{d\Gamma(E)}{dE} = \frac{\alpha(\lambda)}{E}. \tag{5}$$

The obtained values for λ are:

$$\lambda \leq 2.4 \cdot 10^{-18} s^{-1}, \tag{6}$$

if no mass dependence is considered, and

$$\lambda \leq 8.1 \cdot 10^{-12} s^{-1}, \tag{7}$$

in the mass proportional CSL assumption. The results was published in Entropy 19 (7) (2017) 319.

By using a similar method, we are considering the idea to perform a dedicated experiment at LNGS which will allow for 1 - 2 orders of magnitude further improvement on the collapse rate parameter λ.

4.1 Workshops organization

In 2017 the following events related to the physics of VIP, and, more generally, to quantum mechanics, were organized:

1. Workshop Quantum Foundation, "The physics of "what happens" and the measurement problem", 24-26 May, 2017, Frascati, Italy.
2. Workshop Quantum Foundation, "New frontiers in testing quantum mechanics from underground to the space", 29 November-1 December, 2017, Frascati, Italy.

5 Activities in 2018

In 2018 we will be in data taking with VIP2 at LNGS-INFN. The 2016 and 2017 data analysis will be finalized and published. We are, as well, going to 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) model.

Acknowledgements

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6 Publications in 2017

1. Catalina Curceanu *et al*, Quantum mechanics under X-rays in the Gran Sasso underground laboratory, Int. J. Quant .Inf. **15** (2017) no.08, 1740004.
2. B. Jasinska *et al*, Human Tissues Investigation Using PALS Technique, Acta Phys. Polon. B **48** (2017) 1737.
3. J. Marton *et al*, VIP2 at Gran Sasso - Test of the validity of the spin statistics theorem for electrons with X-ray spectroscopy, arXiv:1711.01309.
4. M. Mohammed *et al*, A Method to Produce Linearly Polarized Positrons and Positronium Atoms with the J-PET Detector, Acta Phys. Polon. A **132** (2017) 1486.
5. L. Raczynski *et al*, Introduction of total variation regularization into filtered backprojection algorithm, Acta Phys. Polon. B **48** (2017) 1611.
6. S. Niedzwiecki *et al*, J-PET: a new technology for the whole-body PET imaging, Acta Phys. Polon. B **48** (2017) 1567.
7. E. Czerwinski *et al*, Commissioning of the J-PET detector for studies of decays of positronium atoms, Acta Phys. Polon. B **48** (2017) 1961.
8. R.Y. Shopa *et al* , Three-dimensional image reconstruction in J-PET using Filtered Back Projection method, Acta Phys. Polon. B **48** (2017) 1757.
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10. M. Skurzok *et al*, Time calibration of the J-PET detector, Acta Phys. Polon. A **132** (2017) no.5, 1641.
11. L. Raczynski *et al*, Calculation of time resolution of the J-PET tomograph using the Kernel Density Estimation, Phys. Med. Biol. **62** (2017) 5076.
12. Catalina Curceanu *et al*, Test of the Pauli Exclusion Principle in the VIP-2 underground experiment, Entropy **19** (2017) no.7, 300.

13. J. Marton *et al*, Underground test of quantum mechanics - the VIP2 experiment, arXiv:1703.10055 [quant-ph].
14. Catalina Curceanu *et al* , Underground tests of quantum mechanics. Whispers in the cosmic silence?, J. Phys. Conf. Ser. **880** (2017) no.1, 012045.
15. J. Marton *et al*, VIP-2 at LNGS: An experiment on the validity of the Pauli Exclusion Principle for electrons, J. Phys. Conf. Ser. **873** (2017) no.1, 012018.
16. K. Piscicchia, *et al*, CSL Collapse Model Mapped with the Spontaneous Radiation, Entropy 2017, 19(7), 319.

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