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, ($P < 1.7 \times 10^{-26}$ 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 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.)

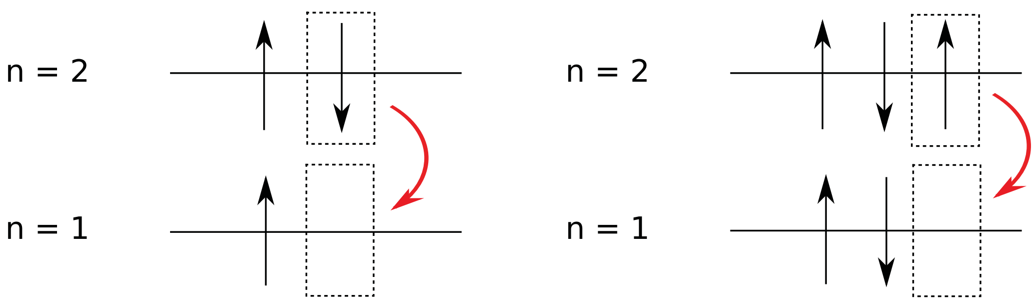

Figure 1: *Normal 2p to 1s transition with an energy around 8 keV for Copper (left) and Pauli-violating 2p to 1s transition with a transition energy around 7,7 keV in Copper (right).*

The 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.

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.

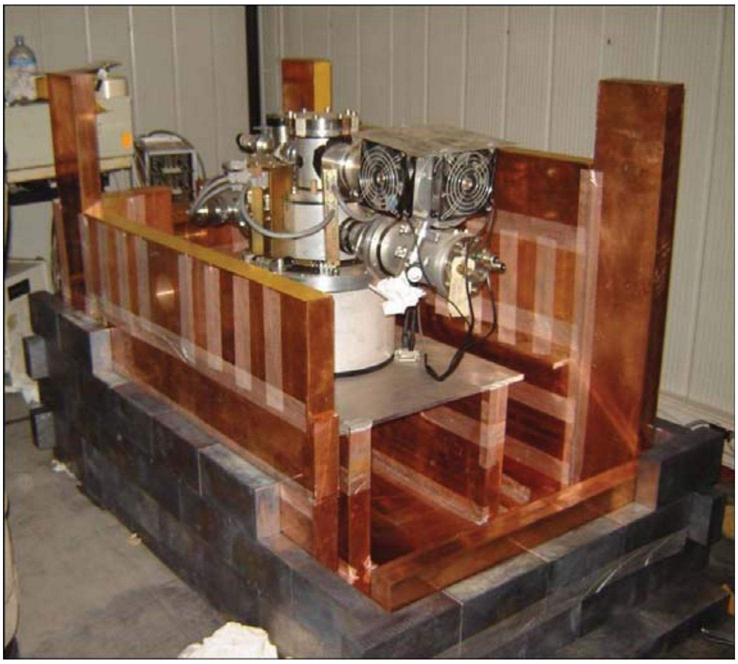

Figure 2: The VIP setup at the LNGS laboratory during installation.

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 2016

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 2016

In the VIP2 apparatus six SDDs units, with a total active area of 6 cm^2 each are mounted close to the Cu target, giving an acceptance which is about ten times as large as the acceptance of VIP

CCDs. 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 year 2016, 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.

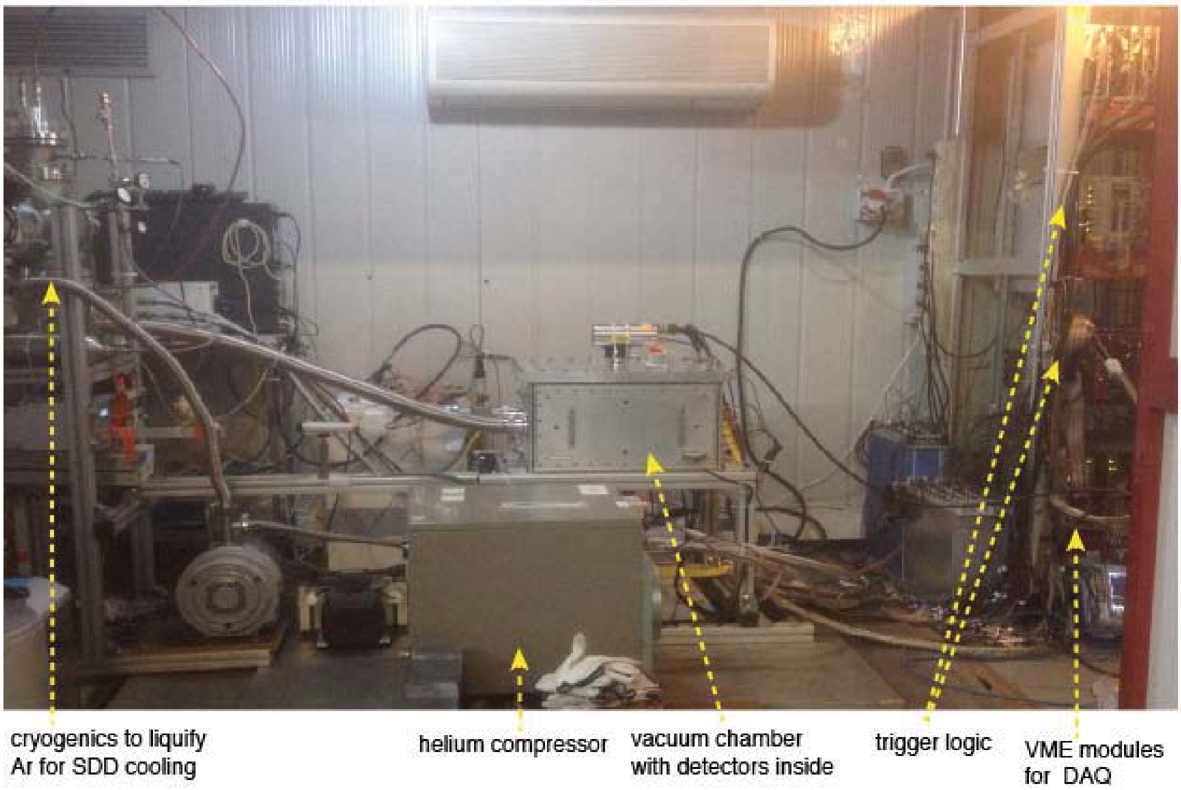

Figure 3: *A picture of the VIP-2 setup installed at LNGS .*

Data with 100 Ampere DC current applied to the copper strip was collected together with the data collected without current. A preliminary analysis of the two spectra to determine a new value of the upper limit for PEP violation is on going. Figure 4 shows the summation of the data from 2016 of all the SDDs for 34 days of data taking with current and for 28 days without current. The preliminary analysis shows the energy resolution of the summed spectra at 8 keV is less than 190 eV FWHM.

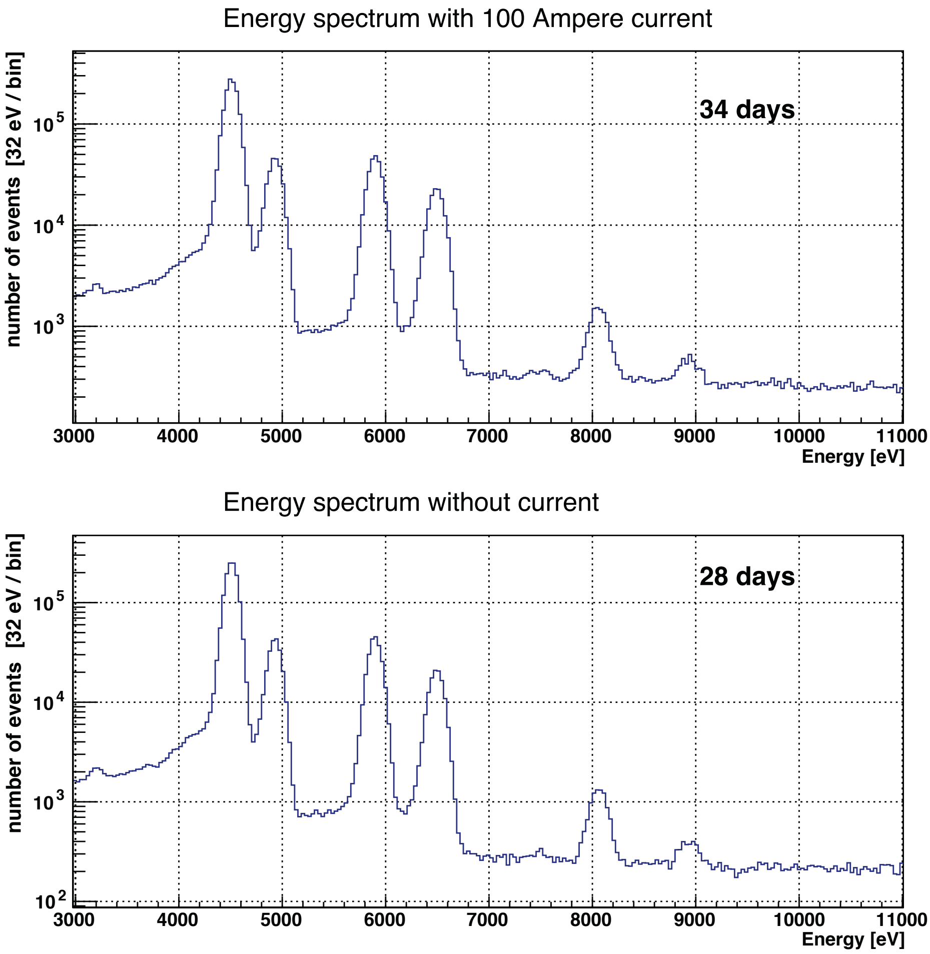

Figure 4: *Upper figure: the energy spectrum obtained by VIP2 in 34 days with current (I=100 A); Lower figure: the energy spectrum obtained by VIP2 in 28 days without current.*

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:

$$\frac{d\Gamma(E)}{dE} = \frac{e^2\lambda}{4\pi^2 a^2 m^2 E} \tag{1}$$

in eq. (1) 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. (1), Fu obtained the following upper limit for λ (non-mass poportional model):

$$\lambda < 0.55 \cdot 10^{-16} s^{-1}. \tag{2}$$

In eq. (2) 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 ~ 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. 4 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 $\beta\beta0\nu$ 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. (1)).

A Bayesian model was adopted to calculate the χ^2 variable minimized to fit the X ray spectrum, assuming the predicted (Eq. (1)) energy dependence:

$$\frac{d\Gamma(E)}{dE} = \frac{\alpha(\lambda)}{E}. \tag{3}$$

The obtained values for λ are:

$$\lambda \leq 2.5 \cdot 10^{-18} s^{-1}, \tag{4}$$

if no mass dependence is considered, and

$$\lambda \leq 8.5 \cdot 10^{-12} s^{-1}, \tag{5}$$

in the mass proportional CSL assumption. This analysis improves the previous limit [7] of two orders of magnitude.

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 2016 the following events related to the physics of VIP, and, more generally, to quantum mechanics, were organized:

1. Training school for graduating students, PhD students and young researchers, "Are spin-statistics and quantum theory exact?", LNF-INFN, December 19-21, 2016.
2. Testing the limit of quantum superposition principle in nuclear, atomic and optomechanical systems, ECT*, Trento, 11-16 September 2016.

Also, VIP was included in about 20 lectures given by Catalina Curceanu in Australia, as Women in Physics Lectures award for 2016, awarded by the Australian Institute of Physics.

5 Activities in 2017

In 2017 we will be in data taking with VIP2 at LNGS-INFN. The preliminary 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.

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6 Publications in 2016

1. M. Pawlik-Niedwiecka *et al*, J-PET detector system for studies of the electron-positron annihilations, EPJ Web Conf. **130** (2016) 07020.
2. P. Moskal *et al*, Studies of discrete symmetries in a purely leptonic system using the Jagiellonian Positron Emission Tomograph, EPJ Web Conf. **130** (2016) 07015.
3. D. Daminska *et al*, A feasibility study of ortho-positronium decays measurement with the J-PET scanner based on plastic scintillators, Eur. Phys. J. C **76** (2016) no.8, 445.
4. P. Moskal *et al*, Potential of the J-PET detector for studies of discrete symmetries in decays of positronium atom - a purely leptonic system, Acta Phys. Polon. B **47** (2016) 509 .
5. A. Pichler *et al*, Application of photon detectors in the VIP2 experiment to test the Pauli Exclusion Principle, J. Phys. Conf. Ser. **718** (2016) no.5, 052030.

6. C. Curceanu *et al*, Spontaneously emitted X-rays: an experimental signature of the dynamical reduction models, Found. Phys. **46** (2016) 263.

7. H. Shi *et al*, Searches for the Violation of Pauli Exclusion Principle at LNGS in VIP(-2) experiment, J. Phys. Conf. Ser. **718** (2016) no.4, 042055 .

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