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, ($P < 1.7 \times 10^{-26}$ 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 (Figure 1).

The energy of 2p → 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 and 2021 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).

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

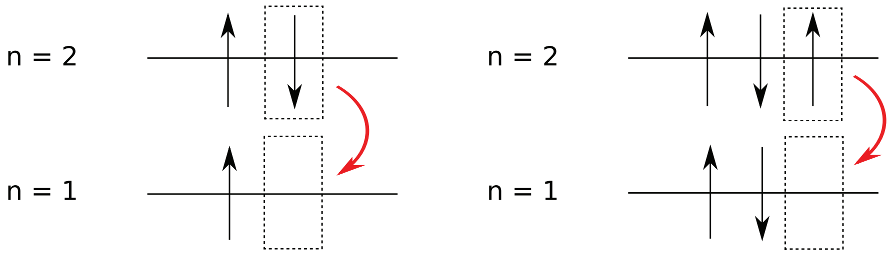

Figure 1: *Normal 2p to 1s transition with an energy around 8 keV for Copper (left) and Pauli-violating 2p to 1s transition with a transition energy around 7,7 keV in Copper (right).*

The VIP group has extended its scientifc 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 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, 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.

3 Activities in 2021

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

- signal increase with a more compact system with higher acceptance and higher current flow in the new copper strip target;

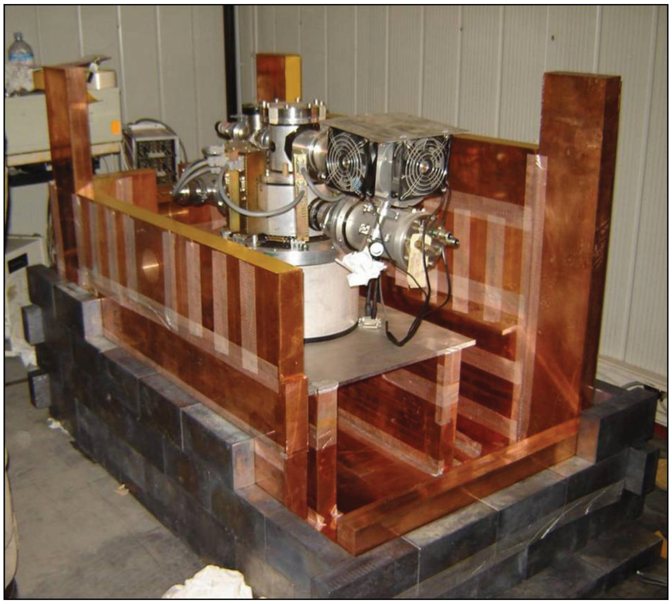

Figure 2: *The VIP setup at the LNGS laboratory during installation.*

- background reduction by decreasing the X-ray detector surface and by using a more compact shielding (active veto system and passive).

3.2 Status of VIP-2 in 2021

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 2022, data with 180 Ampere DC current applied to the copper strip was collected together with the data collected without current, representing the background till summer 2021. In autumn, while VIP barrak is being restructured, a major maintenance is being performed. The data analysis is ongoing and a paper in preparation.

3.3 VIP-2 data analyses in 2021

During 2021 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.

By applying these methods a new limit of PEP violation was obtained as (preliminary):

$$\frac{\beta^2}{2} \leq 1.1 \times 10^{-42} \tag{1}$$

presently under submission to a pre-reviewed journal. Discussions with theoretician about the interpretation of results, in particular in the framework of Quantum Gravity models, are ongoing.

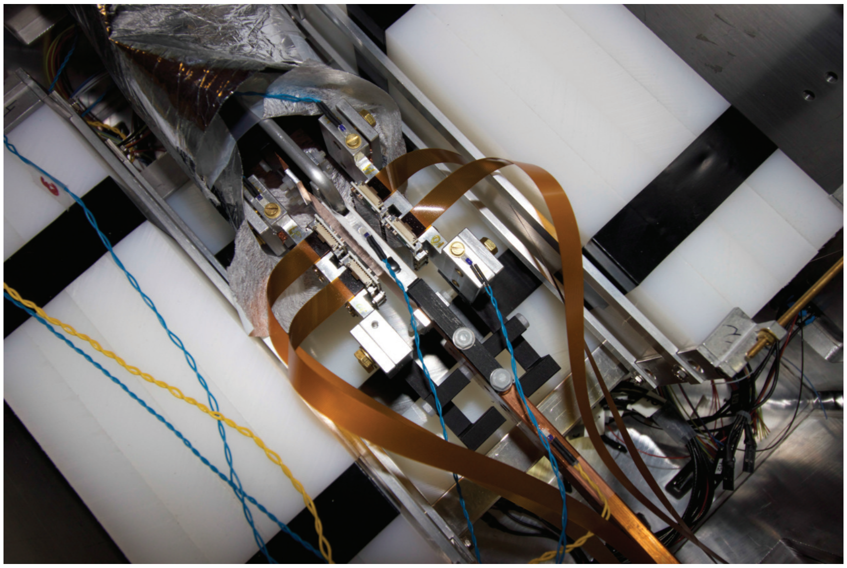

Figure 3: *TA picture of the inner part of the VIP-2 setup with the new SDDs installed at LNGS.*

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

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 and a correlation length a $= 10^{-7}$ m. Between two localizations particles evolve according to the Shrodinger 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 Shrodinger 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 $10^{-17}\mathrm{s}^{-1}$ 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 nonrelativistic 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):

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

In eq. (3) the QMSL value for a ($a = 10^{-17}$ 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 $\lambda < 2 \times 10^{-16} s^{-1}$.

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 R0 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.

In 2021 we further improved also our results on CSL model, and, published it in Eur. Phys. J.C **81** 8, 773 (2021): $\lambda < 5.2 \times 10^{-13}$ s^{-1}.

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, and in 2021 a JTF (John Templeton Foundation) grant.

4.1 Events organization in 2021

In 2021 the following events related to the physics of VIP, and, more generally, to quantum mechanics, was organized:

- Symposium: Fundamental physics with exotic atoms and radiation detectors (online), 25-26 November 2021 (LNF-INFN).
- Symposium: Quantum Boundaries Gravity-Related Collapse Models, 22 December 2021 (LNF-INFN).
- Nuclear and atomic transitions as laboratories for high precision tests of Quantum Gravity insipired models, 27-29 July 2021 (FBK-ECT*, Trento).

5 Activities in 2022

In 2022 we will be in data taking with VIP-2 at LNGS-INFN. The data analysis will be finalized and published. In parallel, a new setup VIP-3, with 1mm thick SDDs will be used and a silver target is being under preparation for a future run to start in 2023. 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

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6 Publications in 2021

1. R. Kaltenbaek, C. Curceanu *et al* ,MAQRO – BPS 2023 Research Campaign Whitepaper,e-Print: 2202.01535 [quant-ph].
2. P. Moskal, C. Curceanu *et al*, Testing CPT symmetry in ortho-positronium decays with positronium annihilation tomography, Nature Commun. 12 (2021) 1, 5658.
3. R.Y. Shopa, C. Curceanu *et al*, Optimisation of the event-based TOF filtered back-projection for online imaging in total-body J-PET, e-Print: 2107.12750 [physics.med-ph].
4. S. Donadi, K. Piscicchia, C. Curceanu *et al*, Novel CSL bounds from the noise-induced radiation emission from atoms, Eur.Phys.J.C 81 (2021) 8, 773.
5. P. Moskal, C. Curceanu *et al*, Simulating NEMA characteristics of the modular total-body J-PET scanner—an economic total-body PET from plastic scintillators, Phys.Med.Biol. 66 (2021) 17, 175015.
6. K. Piscicchia *et al*, γ-ray high sensitivity tests of Collapse Models,J.Phys.Conf.Ser. 2156 (2021) 1, 012167.
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9. K. Dulski, C. Curceanu *et al*, The J-PET detector—a tool for precision studies of ortho-positronium decays, Nucl.Instrum.Meth.A 1008 (2021) 165452.
10. P. Moskal, C. Curceanu *et al*, Positronium imaging with the novel multiphoton PET scanner, Science Advanced,7, 42 (2021), doi: 10.1126/sciadv.abh4394
11. P. Moskal, C. Curceanu *et al*, Testing CPT symmetry in ortho-positronium decays with positronium annihilation tomography, Nature Communications, 12, 5658 (2021).

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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.