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**Abstract.** The VIP collaboration is performing high precision tests of the Pauli Exclusion Principle for electrons in the extremely low cosmic background environment of the Underground Gran Sasso Laboratories of INFN (Italy). The experimental technique consists in introducing a DC current in a copper conductor, searching for the X-rays emission due to a PEP-forbidden atomic transition from the L shell to the K shell of copper when the K shell is already occupied by two electrons. VIP set un upper limit on the PEP violation probability $\frac{1}{2}\beta^2 < 4.7 \times 10^{-29}$, the aim of the upgraded VIP-2 experiment is to improve this result by two orders of magnitude at least. The experimental setup and the results of preliminary data analyses will be presented.

## 1. Introduction

The VIP-2 experiment aims to test the Pauli Exclusion Principle (PEP) for electrons, searching for PEP-violating transitions in copper atoms with high precision X-rays detectors. The PEP states that two identical fermions can not occupy the same quantum state simultaneously and it is one of the fundamental cornerstones of the quantum physics. Its validity guarantees, for instance, the stability of atoms and nuclei, allowing to explain a wide range of phenomena in biology, chemistry and physics. The PEP is directly related to the more general symmetrization postulate and spin-statistic theorem, which describe the quantum states of many-boson and

many-fermion systems. It can be demonstrated within Quantum Field Theory (QFT) that quantum states of identical bosons are symmetric with respect to their permutation and, conversely, quantum states of identical fermions are antisymmetric with respect to their permutation. In addition, the Messiah-Greenberg (MG) superselection rule [1] forbids transitions between different symmetry states in a given system of identical particles, therefore any experimental evidence for a violation of PEP (which is equivalent to a violation of the spin-statistic theorem) would imply the existence of particles that follow other statistics than fermionic and bosonic ones. Hence, even a tiny violation of the PEP, whose probability is usually quantified by means of the $\beta^2/2$ parameter [2, 3], would set the basis for a new physics beyond the Standard Model.

The experimental technique adopted in VIP (see Refs. [4–6]) was pioneered by Ramberg and Snow (see Ref. [7]) to test the PEP for electrons and to fulfill the MG superselection rule. The method consists in circulating a DC current in a copper conductor and to search for the X-rays signature of PEP-violating $K_\alpha$ transitions ($2p \rightarrow 1s$ in Cu when the $1s$ level is already occupied by two electrons). The $K_\alpha$ violating transition is shifted of about 300 eV with respect to the standard $K_\alpha$ line due to the shielding effect of the two electrons in the ground state and is then distinguishable in precision spectroscopic measurements. The method allows to unveil an eventual anomalous symmetry state of the quantum system made of the injected electrons and the atomic electrons since the newly injected electrons have never had before the possibility to perform the searched violating $K_\alpha$ transition in the target Cu atoms. Investigating an open system is a crucial feature in order to test a violation of PEP consistently with the MG superselection rule.

In the present work the upgraded VIP-2 experimental apparatus (see Refs. [8, 9]) will be presented and the results of preliminary data analyses will be described. As will be shown VIP-2 already improved the upper limit imposed by VIP on $\beta^2/2$ (after three years of data taking), which represents the best limit ever on the PEP violation probability for electrons. The final goal of VIP-2 (which is presently acquiring data) is to either further improve the limit of two orders of magnitude, or to measure a signal of PEP violation.

## 2. The VIP-2 experimental apparatus

The VIP experiment set the best limit on the PEP violation probability for electrons $\frac{1}{2}\beta^2 <4.7 \times 10^{-29}$ [4] exploiting the extremely low cosmic background environment of the Underground Gran Sasso Laboratories (LNGS) of INFN. The goal of VIP-2 is to improve the result obtained by VIP of two orders of magnitude at least. To this end the experimental setup has been upgraded as described below (see Fig. 1):

- improvement of the energy resolution at the anomalous transition energy 7746.73 eV (see Ref. [9]). The VIP experiment made use of Charge Coupled Devices (CCDs) as the X-ray detectors, characterised by a Full Width at Half Maximum (FWHM) of 320 eV at 8 keV. The CCDs are replaced by Silicon Drift Detectors (SDDs) with a better energy resolution (190 eV FWHM at 8 keV);

- new geometry to increase the acceptance for the detection of the X-rays. The new layout of the copper target consists of two strips of copper (with a thickness of 50 $\mu$m, and a surface of 9 cm $\times$ 2 cm);

- a cooling pad (cooled down by a closed chiller circuit) is placed in between the two strips in order to avoid the temperature rise due to the heat dissipation in copper. This also allows to enhance the DC current circulating on the strips to 100 A (instead of the 40 A in VIP) thus increasing the candidate event pool for the anomalous X-rays;

- an active shielding system is introduced to remove the background originating from the high energy charged particles that are not shielded by the rocks of the Gran Sasso mountains.

This veto system is made of 32 plastic scintillator bars (250 mm × 38 mm × 40 mm bar) surrounding the SDDs. The light output of each scintillator is read out by two silicon photomultipliers (SiPMs) coupled to each end of the bars;

- all the detectors and the front end preamplifier electronics are mounted inside the vacuum chamber which is kept at $10^{-5}$ mbar during operation;

- in order to perform quick energy calibration and SDDs resolution measurements an X-ray tube on top of the setup irradiates Zirconium and Titanium foils, to produce fluorescence reference lines. A Kapton window in the vacuum chamber and an opening solid angle in the upper scintillator bars, allow to collect in one hour enough statistics for the SDDs performance monitoring. A secondary energy calibration method of the SDDs is performed by means of a weakly radioactive Fe-55 source, with a 25 $\mu$m thick Titanium foil attached on top, mounted together inside an aluminium holder.

The VIP-2 experimental apparatus was transported and mounted in the LNGS at the end of 2015. Following a period of tuning and optimisation a first campaign of data taking started from October 2016 with the complete detector system (except the passive shielding). The analysis of the data collected till the end of 2016 (34 days with a 100 A DC current and 28 days without current) is described in the next section. The data were acquired by means of two arrays of $1 \times 3$ SDDs surrounding the copper target, each array with 3 cm$^2$ of effective surface. The SDDs were cooled down to - 170 °C with circulating liquid argon in a closed cooling line. With a current of 100 A circulating in the strips, their temperature rises up by about 20 °C, inducing a temperature rise at the SDDs of about 1 K, which does not significantly alters the SDDs performances. The six SDDs have an overall 2 Hz trigger rate, accumulating events of fluorescence X-rays from titanium and manganese to calibrate the digitised channel into energy scale.
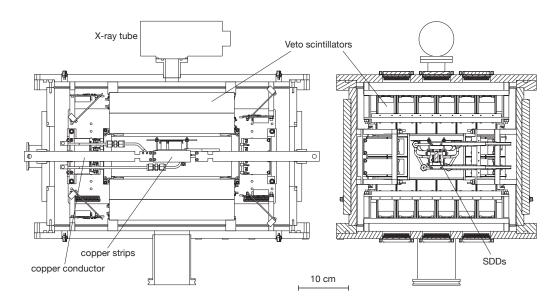


**Figure 1.** The side views of the design of the core components of the VIP-2 setup, including the SDDs as the X-ray detector, the scintillators as active shielding with silicon photomultiplier readout.

A further upgrade of the VIP-2 setup was performed in April 2018:

- the SDDs arrays were replaced with two arrays 2×8 for a total of 32 SDDs;

- new thinner (25 $\mu$m) copper targets were realised, in order to reduce the X-rays absorption inside the target.

The energy calibrated spectra corresponding to a data collection period of 39 days with current, during 2018, are shown in Fig. 3 (without current left, with current right, the first spectrum is normalised to the 39 days of data taking with current). The results of a preliminary analysis, performed on this data set will be shown in Section 3.

In November 2018 the final configuration of the VIP-2 experimental apparatus (shown in Fig. 2) was completed with the passive shielding, this is made of two layers of lead and copper blocks which will kill most of the background due to environmental gamma radiation.

More details on the VIP-2 setup, the trigger logic, data acquisition and slow control can be found in Ref. [9].
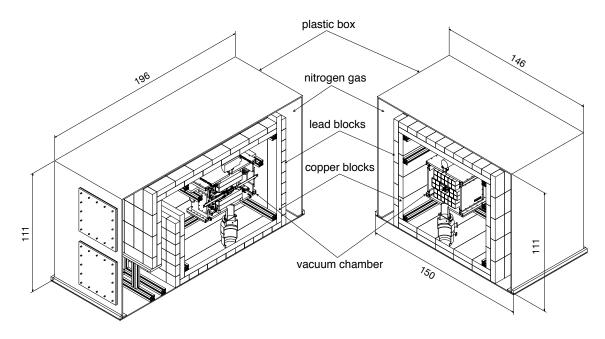


**Figure 2.** Perspective views of the VIP-2 apparatus with passive shielding, with the dimensions in cm. Nitrogen gas with a slight over pressure with respect to the external air will be circulated inside a plastic box in order to reduce the radon contamination.
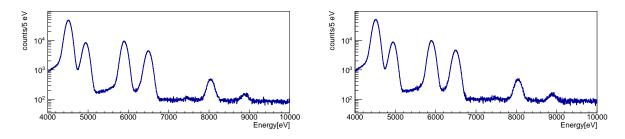


**Figure 3.** Energy calibrated spectra corresponding to 39 days of data taking (during 2018) with current on (right), the spectrum collected with current off (left) is normalised to the 39 days of data taking with current.

## 3. Data analysis

A simultaneous $\chi^2$ fit of two spectra, corresponding to the data acquisition with and without current, was performed in order to put in evidence an eventual signal of PEP violating $K_\alpha$ transitions; the spectra and the obtained fit result are shown in Fig. 4. The $\chi^2$ minimisation was performed using the MINUIT package of the CERN ROOT software framework [10]; the global $\chi^2$ function is obtained as the product of the likelihoods corresponding to the two spectra, assuming the measurement errors to be distributed according to Gaussians.

The fit proceeds in two steps: as first (see Fig. 4a) a wide energy range is used (from 3.5 keV to 11 keV) in order to exploit the high statistics titanium and manganese lines to determine the Fano Factor and the Constant Noise (an energy independent contribution to the energy resolution). The parameters obtained from this pre-fit are then used as an input for the second fit in the range from 7 keV to 11 keV (see Fig. 4b top), from which the shape of the continuous background near the interesting transition is better determined. The fit parameters accounting for the detector energy resolution, the shape of the continuous background, the shape of the fluorescence peaks, are common for the spectra with and without current. The parameters representing the intensities of the fluorescence peaks and of the continuous background are separately defined. For the current on spectrum an additional Gaussian component was introduced representing the eventual PEP violating $K_\alpha$ transition line, the centre of the line was set at 7746.73 eV (see Refs. [9,11]). In Fig. 4b bottom the residuals from the second fit are shown for the two spectra.

From the fit the number of candidate PEP violating events, contributing to the $K_\alpha$ violating transitions, is obtained, together with the corresponding statistical error:
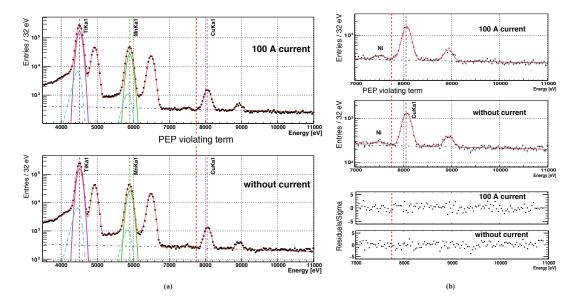


**Figure 4.** A global chi-square function was used to fit simultaneously the spectra with and without 100 A current applied to the copper conductor. The energy position for the expected PEP violating events is about 300 eV below the normal copper $K_{\alpha 1}$ transition. The Gaussian function and 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 details.

$$N_X = 54 \pm 67 \ (statistical). \tag{1}$$

Following the original limit estimated by Ramberg and Snow in Ref. [7] $N_X$ can be related to the PEP violation probability $\frac{1}{2}\beta^2$ as follows:

$$N_X \geq \frac{1}{2}\beta^2 \cdot N_{\text{new}} \cdot \frac{1}{10} \cdot N_{\text{int}} \cdot \epsilon \,, \tag{2}$$

where $N_{\text{new}} = (1/e)\int_{\Delta t} I(t)dt$ is the number of current electrons injected in the copper target over the acquisition time period (with current) $\Delta t$, the factor $1/10$ accounts for the capture probability (per electron-atom scattering) into the $2p$ state (see Ref. [12]), $N_{\text{int}} = D/\mu$ is the minimum number of electron-atom scatterings, where $D$ is the effective length of the copper strip and $\mu$ the scattering length for conduction electrons in the copper strip, $\epsilon = 1.8\%$ is the detection efficiency factor obtained by means of a Monte Carlo (MC) simulation (as described in [9]). By substituting $\mu = 3.9 \times 10^{-6}$ cm, $e = 1.602 \times 10^{-19}$ C, $I = 100$ A, and the effective length of the copper strip $D = 7.1$ cm (the same used in the MC simulation), using the three sigma upper bound of $3 \cdot \Delta N_X = 201$ to give a 99.7% C.L., the following upper limit is obtained for the PEP violation probability:

$$\frac{\beta^2}{2} \leq 3.4 \cdot 10^{-29}. \tag{3}$$

A preliminary analysis of the data collected during 2018 (shown in Fig 3) was performed in analogy to the works described in Refs. [4, 6–8]. A Region of Interest $\Delta E = (7648 \div 7848)$eV is defined, based on the SDDs energy resolution, centred on the energy of the PEP violating transition. In order to obtain the number of candidate violating PEP events in the ROI, the spectrum collected with current off was normalised to 39 days of data collection time with 100 A current on, then the two spectra were subtracted (the resulting subtracted spectrum is shown in Figure 5).

The measured numbers of X-rays in the ROI are:

- with I = 100 A; $N_X = 4103 \pm 64$;
- normalised spectrum with I = 0 A; $N_X = 4010 \pm 63$;
- subtracted number of events $\Delta N_X = 93 \pm 90$.

Using again a three sigma upper bound of $3 \cdot \Delta N_X = 270$ (and considering the improved efficiency $\epsilon = 4\%$) a new preliminary upper limit is obtained for the PEP violation probability:

$$\frac{\beta^2}{2} \leq 1.6 \cdot 10^{-29}. \tag{4}$$



**Figure 5.** Spectrum obtained by subtracting in the ROI region the normalised spectra measured during 2018 with and without current.

## 4. Discussion and Perspectives

The limit obtained in Eq. 3 (and the preliminary limit in 4) assumes, in analogy with the analysis performed by Ramberg and Snow, a very simple straight path of the electrons across the Cu target strip. The number of electron capture processes is then estimated using the scattering length of the electrons in the Cu conductor (the average scattering time is $2.5 \times 10^{-14}$ s).

In Ref. [13] it is argued that scatterings are not actually related to the atoms themselves, but depend on impurities, lattice imperfections and on phonons. In Ref. [13] scatterings are then replaced with the "close encounters" among electrons and atoms and the random walk of the electrons, as they move from the entrance to the exit of the copper target, is described. This complex walks bring the electrons close to many more atoms than in the scattering picture. The mean time between close electron-atom encounters is evaluated in Ref. [13] and it is found to be $3.5 \times 10^{-17}$ s, much shorter than the average scattering time. Considered the traversal time of the copper target (which is estimated in [13] to amount to 10 s for the setup described in Section 2) an improved limit is obtained on the PEP violation probability: $\frac{\beta^2}{2} \leq 2.6 \cdot 10^{-40}$ (an improved limit $\frac{\beta^2}{2} \leq 1.0 \cdot 10^{-40}$ is obtained from the preliminary analysis of the data collected in 2018).

The analysis presented in Ref. [13] for the random walk which electron undergo in crossing the copper target material is mostly classical. We are presently working to extend the calculation to the quantum domain.

## References

[1] Messiah A and Greenberg O 1964 *Physical Review* **136** B248
[2] Ignatiev A Y and Kuzmin V 1987 *Quarks 86: Proceedings of the Seminar, Tbilisi, USSR, 15-17 April 1986* (VNU Science Press BV: Utrecht, The Netherlands: Tavkhelidze, A.N.; Matveev, V.A.; Pivovarov, A.A.; Tkachev, I.I., Eds.)
[3] Ignatiev A Yu 2006 *Radiat. Phys. Chem.* **75** 2090–2096 (*Preprint* `hep-ph/0509258`)
[4] Curceanu Petrascu C *et al.* 2011 *J. Phys. Conf. Ser.* **306** 012036
[5] Bartalucci S *et al.* 2010 *Found. Phys.* **40** 765–775
[6] Sperandio L 2008 *New experimental limit on the Pauli Exclusion Principle violation by electrons from the VIP experiment* Ph.D. thesis Tor Vergata University Rome
[7] Ramberg E and Snow G A 1990 *Physics Letters B* **238** 438–441
[8] Curceanu C *et al.* (VIP) 2017 *Entropy* **19** 300
[9] Shi H *et al.* 2018 *Eur. Phys. J.* **C78** 319
[10] Brun R and Rademakers F 1997 *Nucl. Instrum. Meth.* **A389** 81–86
[11] Curceanu C *et al.* 2013 *INFN Technical Report* **INFN-13-21/LNF**
[12] Bartalucci S *et al.* 2006 *Phys. Lett.* **B641** 18–22
[13] Milotti E *et al.* 2018 *Entropy* **20** 515