

TESTING THE PAULI EXCLUSION PRINCIPLE IN THE COSMIC SILENCE*

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(Received October 31, 2019)

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 K_α PEP-forbidden atomic transitions when the K shell is already occupied by two electrons. VIP set an 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 at least by two orders of magnitude. The improved experimental setup and the results of a preliminary data analysis, corresponding to the the first run of the VIP-2 data taking (2016–2017), will be presented.

DOI:10.5506/APhysPolB.51.97

* Presented at the 3rd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics, Kraków, Poland, June 23–28, 2019.

1. Introduction

The VIP-2 experiment aims to perform high sensitivity tests of the Pauli Exclusion Principle (PEP) for electrons, searching for PEP-violating transitions in copper atoms with high precision X-rays detectors. PEP is a pilaster of the Standard Model of particle physics and underpins our explanation of the matter stability, being responsible for a plethora of phenomena which range from the arrangement of the elements in the periodic table to the stability of neutron stars. The PEP was first formulated by Fierz [1] and then comprehensively demonstrated by Pauli (see, for example, [2]). The Symmetrization Postulate, describing the quantum states of many-boson and many-fermion systems, can be proven in the context of relativistic quantum field theory (QFT) on the basis of few, very general, assumptions, such as: (i) Lorentz/Poncaré and CPT symmetries, (ii) locality, (iii) unitarity, (iv) causality. The spin statistics theorem then appears to be deeply grounded in the very fundamental structure of space and time, as a consequence theories beyond the Standard Model can embed tiny violations of PEP (see *e.g.* [3–6]). The experimental search for PEP violating reactions can then shed new light, either on the fermionic/bosonic nature of the elementary particles, or on the very foundations of QFT.

The “Messiah–Greenberg” (MG) superselection rule [7] shows that transitions among different symmetry states have zero amplitude. Accordingly, a signal from PEP-violating transitions is to be searched in open quantum systems, *e.g.* by looking for transitions among violating states of a system after the introduction of particles from outside of the considered system. Transitions among anomalous states would occur at the standard rate if the involved particles couple universally to the interaction field.

The VIP Collaboration is performing tests of the PEP for electrons [8, 9], in the extremely low background environment of the Gran Sasso National Laboratory (LNGS) of INFN, exploiting a method which fulfils the (MG) superselection rule. The experimental approach was proposed by Greenberg and Mohapatra [5] and pioneered by Ramberg and Snow [10]. The idea is to circulate a Direct Current (DC) in a copper strip conductor and look for anomalous K_α transitions. An anomalous transition may occur if a new electron, injected into the copper strip, forms a wrong symmetry state with the electrons in the inner shell of a copper atom; the electron would be captured by the atom and emit anomalous X-rays as it cascades down to the fundamental level of the non-Paulian atom. The anomalous K_α transition would be shifted towards lower energy of about 300 eV as a consequence of the extra shielding provided by the two electrons residing in the 1s state of the atom (see [9] for the details of the calculation). A reference background spectrum is collected with no circulating current.

Preliminary results of the data analyses, corresponding to the first run of the VIP-2 data taking (2016–2017) are presented. An improved VIP-2 experimental setup was installed in LNGS in (2018–2019) and is presently taking data.

2. The VIP-2 experimental apparatus

The PEP-violation probability is commonly quantified in terms of the $\frac{1}{2}\beta^2$ parameter (see *e.g.* [3, 4]). The goal of VIP-2 is to improve the result obtained by the VIP experiment ($\frac{1}{2}\beta^2 < 4.7 \times 10^{-29}$ [8]) by at least two orders of magnitude. To this end, the experimental setup was improved as described below (see Fig. 1):

- VIP 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 (corresponding to the definition of the Region Of Interest (ROI), around the calculated energy of the PEP-violating transition of 7747 eV, where the signature of anomalous X-ray transitions is searched for). The CCDs were replaced by Silicon Drift Detectors (SDDs) with a better energy resolution (190 eV FWHM at 8 keV);
- the geometric acceptance was increased by reshaping the copper target, which now consists of two strips of copper (with an effective length of 7.1 cm, a height of 2 cm and a thickness of 50 μm each);
- in order to minimise the temperature rise caused by the heat dissipation in copper, a cooling pad was placed between the strips (cooled down by a closed chiller circuit). This allowed to increment the circulating DC current to 100 A (instead of the 40 A in VIP) thus increasing the electron candidate event pool for the anomalous X-rays;
- an active shielding surrounds the target and the SDDs detectors system. This is made of 32 plastic scintillator bars (250 mm \times 38 mm \times 40 mm bar) read out at each end by two silicon photomultipliers (SiPMs). The active veto was conceived to remove the background originating from the high-energy charged particles that are not shielded by the rocks of the Gran Sasso mountains and to suppress the natural radioactivity.
- 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 is performed by means of a weakly radioactive Fe-55 source, with a $25\ \mu\text{m}$ thick titanium foil attached on top, mounted together inside an aluminium holder.

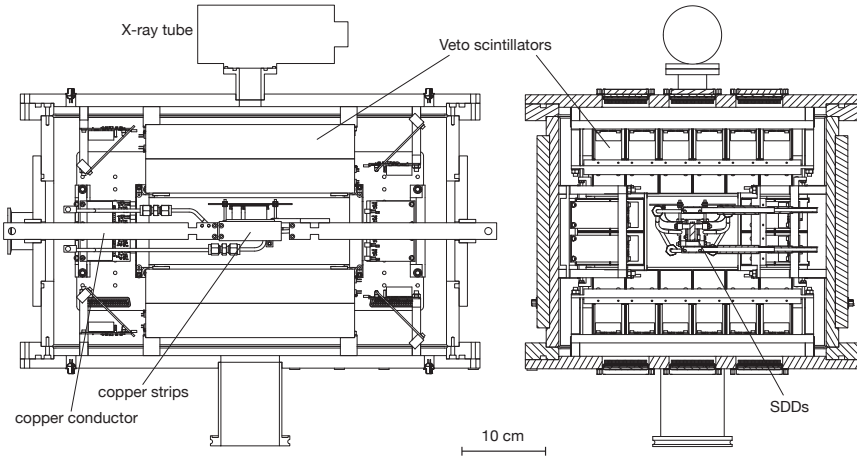


Fig. 1. Side views of the core components of the VIP-2 setup, including the SDDs and the active shielding system.

The VIP-2 experimental apparatus was transported and mounted in the LNGS (Laboratori Nazionali del Gran Sasso) at the end of 2015. After tuning and optimization, a first data taking campaign lasted from October 2016 to the end of 2017. In this configuration, two arrays of 1×3 SDDs were installed surrounding the copper target, each array with an effective surface of $3\ \text{cm}^2$. A liquid argon closed cooling line was used to cool down the SDDs to -170°C . With a current of 100 A circulating in the strips, their temperature rose up by about 20°C , inducing a temperature rise at the SDDs of about 1 K, which does not significantly alter the SDDs performance. 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.

The first data taking run of the VIP-2 experiment is completed. 81 days and 10 hours of data with a current of 100 A were acquired, together with an equivalent period without current, which serves as background reference spectrum. The analysis of this data set will be presented in Section 3. A preliminary analysis of a data sub-set (34 days of data with a 100 A DC current and 28 days without current) can be found in Ref. [9] together with more details on the VIP-2 setup, the trigger logic and the data acquisition system.

A further upgrade of the VIP-2 setup was installed in LNGS in the period of 2018–2019 and is presently taking data, with the following main improvements: *(i)* the SDDs arrays were replaced with two arrays 2×8 for a total of 32 SDDs; *(ii)* new thinner (25 μm) copper targets were realised, in order to reduce the X-rays absorption inside the target; *(iii)* the vacuum chamber was completely surrounded by a passive shielding (an internal copper and an external lead layer) which will eliminate most of the background due to environmental gamma radiation.

3. Data analysis

A preliminary analysis of the first VIP-2 data taking run was performed in analogy to the work described in Refs. [8, 10–12]. A Region Of Interest $\Delta E = (7647 \div 7847)\text{eV}$ 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 events violating PEP in the ROI, the spectrum collected with current off was normalised to the acquisition time with 100 A current on, then the two spectra were subtracted (the resulting subtracted spectrum is shown in Fig. 2).

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

- with $I = 100$ A; $N_X = 4202 \pm 65$;
- normalised spectrum with $I = 0$ A; $N_X = 4105 \pm 64$;
- subtracted number of events $\Delta N_X = 97 \pm 91$.

By setting a three sigma upper bound of $N_{3\sigma} = 273$, a preliminary upper limit is obtained for the PEP-violation probability

$$\frac{\beta^2}{2} \leq \frac{10}{N_{\text{int}}N_{\text{new}}} \frac{N_{3\sigma}}{\epsilon} \leq 1.87 \times 10^{-29}. \quad (1)$$

In Eq. (1), $N_{\text{new}} = (1/e) \int_{\Delta t} I(t)dt$ is the number of current electrons injected in the copper target over the acquisition time period (with current) Δt , the factor 1/10 accounts for the capture probability (per electron–atom scattering) into the $2p$ state (see Ref. [13]), $N_{\text{int}} = D/\mu$ is the minimum number of electron–atom scatterings, where D is the effective length of the copper strip and μ 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 simulation (as described in [9]).

This result improves by a factor of more than 2 the previous limit of VIP. The collaboration is now both improving the apparatus and considering new ideas for novel data analyses. They have the potential to greatly increase the sensitivity of the test, and produce much stricter bounds on violations of the Pauli Exclusion Principle for electrons.

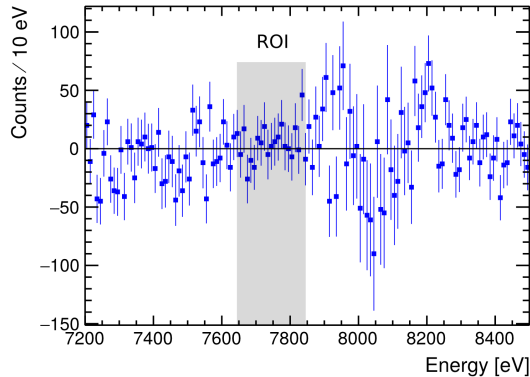


Fig. 2. Spectrum in the ROI region obtained by subtracting the normalised spectra with and without current.

We thank H. Schneider, L. Stohwasser, and D. Pristauz-Telsnigg from Stefan-Meyer-Institut for their fundamental contribution in designing and building the VIP2 setup. We acknowledge the very important assistance of the INFN-LNGS laboratory. We acknowledge the support of the Centro Fermi — Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi” (*Open Problems in Quantum Mechanics project*), the support from the EU COST Action CA 15220 and from the H2020 FET Project TEQ (grant No. 766900). We thank the Austrian Science Foundation (FWF) which supports the VIP2 project with the grants P25529-N20, project P 30635-N36 and W1252-N27 (doctoral college particles and interactions).

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