Vol. 14 (2021) *Acta Physica Polonica B Proceedings Supplement* No 1

HIGH SENSITIVITY QUANTUM MECHANICS TESTS IN THE COSMIC SILENCE*

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(Received September 30, 2020)

The VIP experiment aims to perform 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. The results of a preliminary data analysis, corresponding to the first run of the VIP-2 data taking (2016–2017), are presented. The experimental setup in the final configuration is described together with preliminary spectra from the 2019 data-taking campaign.

DOI:10.5506/APhysPolBSupp.14.151

* Presented at *Excited QCD 2020*, Krynica Zdrój, Poland, February 2–8, 2020.

1. Introduction

The VIP Collaboration is performing high-precision tests of the Pauli Exclusion Principle (PEP) for electrons [1–3] at the Gran Sasso National Laboratory (LNGS) of INFN. The PEP is deeply embedded in our theories of the microscopic world and underpins our explanation of the matter stability, accounting for the arrangement of the elements in the periodic table as well as for the stability of neutron stars. The PEP is a direct consequence of the spin-statistics connection which was first formulated by Fierz [4] and then comprehensively demonstrated by Pauli [5] using few, very general assumptions that lay at the basis of Quantum Field Theory (QFT): *(i)* Lorentz/Poincaré and CPT symmetries, *(ii)* locality, *(iii)* unitarity, *(iv)* causality. Since PEP is grounded in the fundamental structure of space and time, theories beyond the Standard Model can embed tiny violations of PEP (see *e.g.* [6–9]). Therefore, experimental tests of PEP can be viewed either as tests of the fermionic/bosonic nature of the elementary particles, or as tests of the foundations of QFT.

Transitions between states with different symmetry are forbidden even in a world in which the spin-statistics connection is violated, this is a consequence of the Messiah–Greenberg (MG) superselection rule [10]. Accordingly, a signal from PEP violating transitions is to be searched for in the open quantum systems, *e.g.* by looking for transitions among violating states of a system which was prepared introducing particles from outside. If the involved particles couple universally to the interaction field, then transitions among anomalous states occur at the standard rate.

The VIP-2 experiment [2, 3] exploits a method which fulfils the MG superselection rule, such a technique was originally suggested by Greenberg and Mohapatra [11], and a first experiment was performed by Ramberg and Snow [12]. The method consists in circulating a Direct Current (DC) in a copper strip conductor and looking for anomalous K_α transitions. Some of the new electrons injected into the copper strip may form a wrong symmetry state with the electrons in the inner shells of the copper atoms, so that they could be radiatively captured by these atoms and emit anomalous atomic X-rays as they cascade to the fundamental level of non-Paulian atoms. The anomalous K_α transition would be shifted 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 Ref. [3] 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; these provide the best upper limit on the PEP violation probability for electrons, respecting the MG superselection rule. An improved VIP-2 experimental setup was installed in LNGS in (2018–2019) and is presently taking data; preliminary spectra acquired with the upgraded setup are shown.

2. The VIP-2 setup and preliminary results

We express the PEP violation probability in terms of the parameter $\frac{1}{2}\beta^2$ (introduced in [6, 7]) which is commonly used in literature. VIP-2 aims to improve the previous result obtained by VIP ($\frac{1}{2}\beta^2 < 4.7 \times 10^{-29}$ [1]) of at least two orders of magnitude; to this end, the VIP-2 experimental apparatus, which is represented in Fig. 1, was substantially upgraded:

(a) The Charge Coupled Devices (CCDs) X-ray detectors were replaced with Silicon Drift Detectors (SDDs), characterised by a better energy resolution Full Width at Half Maximum (FWHM) of about 190 eV FWHM at 8 keV.

(b) The time resolution of the SDDs is about about 400 ns (FWHM), this allowed the introduction of a veto system made of 32 plastic scintillator bars (250 mm $\times$ 38 mm $\times$ 40 mm bar) surrounding the target and the SDDs, read out at each end by two silicon photomultipliers (SiPMs). The active shielding serves to reduce the background caused by high-energy charged particles that are not shielded by the rocks of the Gran Sasso mountains.

(c) The target was reshaped in order to increase the geometric acceptance, it 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).

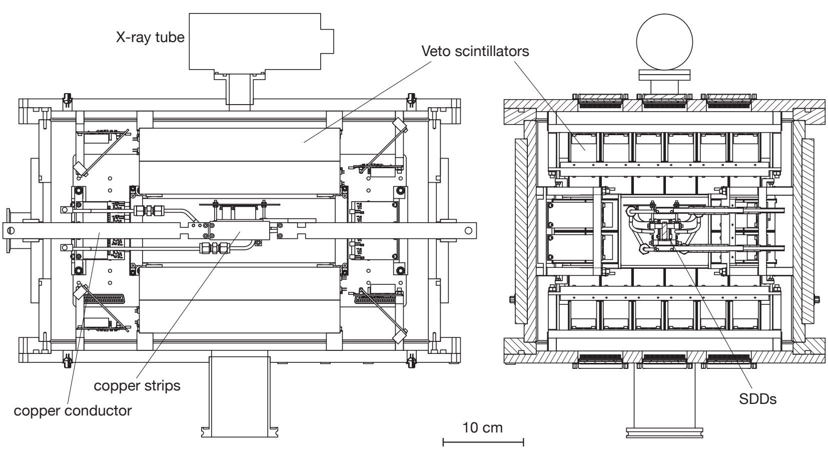

Fig. 1. Side views of the core components of the VIP-2 setup, including the SDDs and the active shielding system.

(d) The target is cooled down by a closed chiller circuit, the lower temperature rise caused by the heat dissipation in copper allowed to increase the circulating DC current from 40 A (in VIP) to 100 A. The higher current traduces in a bigger number of injected test electrons. The SDDs are cooled down to -170°C by a liquid argon closed cooling line, the temperature fluctuation on the SDDs does not exceed 1 K, which does not significantly alters the detectors performances.

(e) The energy calibration is performed by means of a weakly radioactive Fe-55 source, with a 25 μm thick titanium foil attached on top, mounted together inside an aluminium holder. The six SDDs used in the first VIP-2 configuration have an overall 2 Hz trigger rate, accumulating events of fluorescence X-rays from titanium and manganese.

The first configuration of the VIP-2 experiment was mounted in the LNGS at the end of 2015, the detectors system consisted of two arrays of 1×3 SDDs (each array with an effective surface of 3 cm^2) surrounding the copper target. After tuning and optimisation, a first data-taking campaign lasted from October 2016 to the end of 2017; 81 days and 10 hours of data were collected with current on, an equal period was acquired with current off in order to obtain the reference background spectrum.

A preliminary analysis of the first VIP-2 data taking run was performed in analogy to the works described in Refs. [1, 2, 12–14]. The ROI is defined as $\Delta E = (7647 \div 7847)$ eV, based on the SDDs energy resolution. The number of candidate PEP violating events in the ROI is obtained by subtracting the reference background spectrum from the spectrum collected with current on (the spectra are normalised to the acquisition time period with current Δt). The resulting subtracted spectrum is shown in Fig. 2 (left). The measured numbers of X-rays in the ROI are $N_X^{I=100} = 4202 \pm 65$ with current and $N_X^{I=0} = 4105 \pm 64$ without current. By setting a three sigma upper bound $N_{3\sigma} = 273$, the limit on the PEP violation probability is

$$\frac{\beta^2}{2} \leq \frac{10}{N_{\mathrm{int}} N_{\mathrm{new}}} \frac{N_{3\sigma}}{\epsilon} \leq 1.87 \times 10^{-29}\,. \tag{1}$$

In Eq. (1), $N_{\mathrm{new}} = (1/e) \int_{\Delta t} I(t) \mathrm{d}t$ is the number of electrons injected in the target in the period Δt; $N_{\mathrm{int}} = D/\mu$ 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; the factor $1/10$ accounts for the capture probability (per electron–atom scattering) into the $2p$ state (see Ref. [14]); $\epsilon = 1.8\%$ is the detection efficiency factor obtained by means of a Monte Carlo simulation (as described in Ref. [3]).

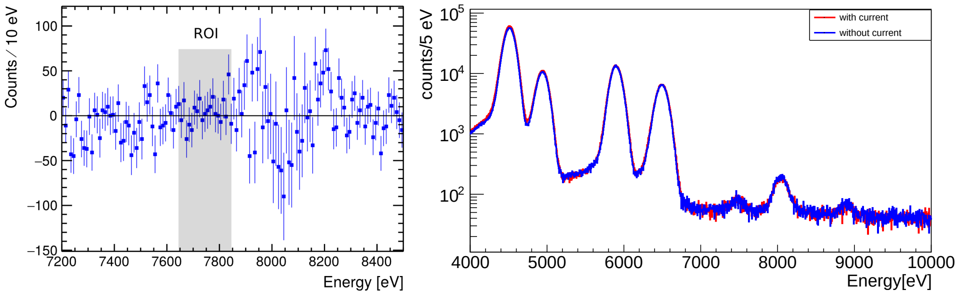

Fig. 2. (Colour on-line) Left: Spectrum obtained by subtracting in the ROI region the normalised spectra with and without current (data 2016–2017). Right: Normalised spectra corresponding to about 90 days of data taking with current on (dark grey/red with current, light grey/blue without current, data 2019).

3. VIP-2 final upgrade and preliminary spectra

The VIP-2 experimental setup underwent a further upgrade in the period of 2018–2019:

(a) The SDDs arrays were replaced with two arrays 2×8 SDDs of 8×8 mm^2 each for a total of 32 SDDs.

(b) In order to reduce the X-rays absorption inside the target, hence improving the efficiency, new copper targets were realised 25 μm thin.

(c) Two layers of passive shielding (an internal copper and an external lead layer) were built, which completely surround the vacuum chamber, in order to further reduce the background due to environmental gamma radiation.

The data acquisition restarted in May 2019; the experiment is presently taking data alternating periods with and without current circulating in the target. The preliminary normalised spectra, corresponding to about 90 days with current on, in the period of May–December 2019, are shown in Fig. 2 (right) (dark grey/red with current, light grey/blue without current). From left to right, the calibration K_α and K_β lines of titanium and manganese are clearly recognisable, followed by the nickel K_α, copper K_α, and copper K_β lines. The aim is to gain two orders of magnitude on the PEP violation probability or, alternatively, to unveil a violation signal.

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*), and from the EU COST Action CA 15220 is gratefully acknowledged. We also acknowledge the support from the H2020 FET Project TEQ (grant No. 766900). We thank the Austrian Science Foundation (FWF) which supports the VIP2 project with the grant P25529-N20, and projects P30635-N36 and W1252-N27 (doctoral college particles and interactions).

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