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Testing the Pauli Exclusion Principle and fundamental symmetries with the VIP underground experiment

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The Pauli Exclusion Principle (PEP) is a fundamental pillar of quantum theory. Potential violations of PEP could indicate physics beyond the Standard Model, including existence of extra dimensions, Lorentz invariance violations, or non-commutative space-time geometries. The VIP Collaboration conducts high precision X-ray spectroscopy experiments at INFN's Gran Sasso Underground National Laboratory to search for atomic transitions that violate PEP. The current VIP-2 experiment, using copper as target material, aims to improve the exclusion limit for PEP violation to $\beta^2/2 < 4 \times 10^{-31}$, enhancing the previous constraint by two orders of magnitude. We present our main experimental results so far, and introduce the upcoming experimental upgrade. Additionally, we discuss the VIP-Lead experiment, which specifically explores PEP violations in lead atoms within the context of Non-Commutative Quantum Gravity frameworks.

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1. Introduction

The Pauli Exclusion Principle (PEP) is a fundamental concept in quantum mechanics, stating that no two identical fermions in a system can occupy the same quantum state simultaneously [1]. The PEP has profound implications across multiple domains of physics, influencing the stability of matter [2], the mechanisms behind superconductivity, and the structure of neutron stars [3]. Its theoretical foundation is rooted in quantum field theory, as first demonstrated by Pauli in the spin-statistics theorem, which dictates how the symmetry properties of a particle's wavefunction depend on its spin, based on a few fundamental assumptions [4, 5].

Violations of the Pauli Exclusion Principle could arise from physics beyond the Standard Model, including Lorentz invariance violation, the existence of extra dimensions, and quantum gravity scenarios [6, 7]. Depending on the theoretical framework, violations could occur in so-called open systems, where a new particle is introduced from outside the system, or in closed systems, where the violation takes place within a stable and fixed set of particles.

According to the Messiah–Greenberg superselection rule [8], transitions between states with different exchange symmetries are forbidden. As a result, PEP violations can only be tested in open systems, where the testing fermion is externally introduced. However, in scenarios involving deformations of space-time, such as in Non-Commutative Quantum Gravity (NCQG), these constraints can be evaded, potentially allowing PEP violations in closed systems [6].

The VIP collaboration conducts high precision X- and gamma-ray spectroscopy at the INFN Gran Sasso Underground Laboratory (LNGS) to search for atomic transitions that violate PEP. In the following sections, we present the experimental efforts of the collaboration, covering both open and closed system approaches, the results obtained so far, and future prospects.

The VIP-2 experiment represents the collaboration's primary effort in the open system framework, aiming to improve the model-independent exclusion limit for PEP violation in copper atoms to $\beta^2/2 < 4 \times 10^{-31}$ (here $\beta^2/2$ historically represents the violation probability). This would enhance the previous constraint by two orders of magnitude [9]. In Section 2, we summarize the main experimental results, and planned upgrades.

The VIP-Lead effort focuses on the closed system scenario, investigating PEP violations in lead atoms within the framework of Non-Commutative Quantum Gravity [10–12]. The experimental setup, results and implications are presented in Section 3.

2. VIP-2 Experiment

The VIP-2 experiment is located at the INFN's underground Gran Sasso National Laboratory, in Italy. With an overburden of more than 3000 meters of water equivalent, the cosmic-ray background is significantly reduced, lowering the cosmic muon flux rate by approximately six orders of magnitude. This low radioactivity environment is an ideal setting to search for tiny effects such as the PEP violation. The experimental methodology is based on the pioneering approach by Ramberg and Snow [15], in which the external fermions (electrons) are introduced to a copper target by means of a high direct current. PEP violation is looked for in anomalous 2p→1s transitions, where the 1s orbital is already fully occupied. The anomalous Kα transition, induced by the PEP-violating electrons, would exhibit a shift due to the additional shielding effect, quantified to be around 300 eV in copper atoms [16]. The PEP-violating transitions are searched in the X-ray spectrum of the copper atoms. VIP-2 has the goal of reaching an exclusion of the PEP violation on $\beta^2/2$ two orders of magnitude better than the precedent VIP experiment. This is possible through the use of state-of-the-art radiation detectors, a bigger target, and a stronger direct current. Silicon Drift Detectors (SDDs) are ideal X-ray detectors, having an excellent spectroscopic response and a resolution of about 190 eV (FWHM) at 8 keV, and were developed in a collaboration between Stefan-Meyer-Institut, Politecnico di Milano, and the Fondazione Bruno Kessler [13, 14].

The VIP-2 experiment has operated following an 'current on-off' scheme in its final configuration since 2019. The data taking is performed in alternating periods with current on (signal) and current off (background). The copper targets are kept at a constant temperature of 15 °C with a dedicated water cooling system. The SDDs are operating at -90 °C and positioned adjacent to the pair of targets. The operational pressure of the vacuum chamber is maintained at 10^{-5} mbar. The spectra obtained with current on and off are shown in Figure 1.

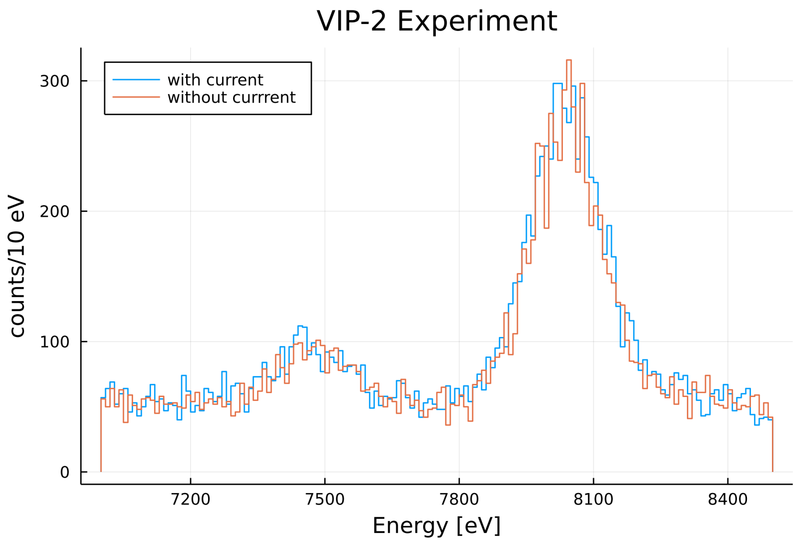

Figure 1: Spectra acquired with current on (blue) and off (orange) by the VIP-2 experiment in approximately six months of data taking in the Region of Interest 7000-8500 eV. The two peak are the nickel Kα and the copper Kα lines, while the signal is expected at around 7700 eV. Reproduced from [9].

The data analysis is performed with a Bayesian and frequentist approach, and the upper limit on the PEP violation is determined through statistical analysis of the data.

Several key factors influence this limit, such as the data taking time, the stability and precision of the calibration, and the detector resolution. The energy calibration of the SDDs is a critical experimental task, and its accuracy is often reflected in the precision of the final spectroscopic observables in the form of systematic uncertainty, often the most relevant. To this end, the collaboration has developed a novel machine learning and differentiable programming enhanced calibration technique to improve the energy resolution of the SDDs [17]. The method has shown to correct for small miscalibrations and to reduce the energy scale uncertainty, improving the physics reach of the VIP-2 experiment.

The first analysis of six months of data taking is presented in [9], with a 180 A direct current circulating in the target for 83 days. The 90% upper limit on the signal yield for the PEP violation was translated into

$$\beta^2/2 < 8.6 \times 10^{-31}\,(\text{Bayesian}), \quad \beta^2/2 < 8.9 \times 10^{-31}\,(\text{frequentist}) \tag{1}$$

While the full dataset is still under analysis, work is ongoing to commission the experimental upgrade VIP-3: the new setup is designed to extend the investigation of PEP violations to different targets made of heavier elements compared to copper. The design of the new setup is outlined in Ref [18]. The VIP-3 setup is under construction, to be installed and start data acquisition at LNGS in 2025, aiming to offer new insights into theories allowing PEP violation. The key experimental parameters upgraded are the use of thicker silicon drift detectors of 1 mm, which will enhance the sensitivity to more energetic X-rays emitted from these heavier elements, and a stronger current of 400 A circulating in the target. The VIP-3 experiment will employ zirconium, silver, palladium, and tin as target materials and features a newly developed setup designed to handle and measure these heavier elements. Additionally, calculations from first principles using the multi-configuration Dirac–Fock method [19] have already been performed to predict energy shifts for the violating transitions in these new targets.

3. VIP-Lead Experiment

The VIP collaboration is also conducting the VIP-Lead experiment to investigate PEP violations in lead atoms, also connected to Non-Commutative Quantum Gravity (NCQG) models. The non-commutativity of space-time is common to several quantum gravity theories; in this context, the PEP violation would be a consequence of effect of the dynamically broken Lorentz symmetry unto the spin statistic theorem.

In the analytic expansion, the PEP violation probability reads [12]:

$$\delta^2 = \left(\frac{E}{\Lambda_k}\right)$$

where E is the energy involved in the atomic transition, the energy scales are expressed as Λ_k, characterizing specific models of space-time non-commutativity. δ^2 accounts for the deformation of the particles' statistics, and the expansion captures the behavior of several different classes of universality of quantum gravity models. In particular the cases corresponding to the selection of $k = 1, 2, 3$, represent the κ-Poincaré ($k = 1$), the θ-Poincaré ($k = 2$) and the triply special relativity ($k = 3$) [20] models.

The measurement was conducted at LNGS, using a coaxial p-type High Purity Germanium (HPGe) detector of about 2 kg in mass, surrounded by 5 cm of radiopure Roman lead. As in the case of the copper target in VIP-2, the PEP-violating transitions are looked for in the X-ray spectrum of the lead atoms. In Figure 2, the spectrum acquired with the germanium detector is shown, with the PEP-violating lead Kα and Kβ lines depicted for clarity.

The data was analyzed with a Bayesian approach, and the 90% upper limit on the signal yield for the PEP violation was translated into the scale of quantum gravity emergence Λ for the different models of NCQG.

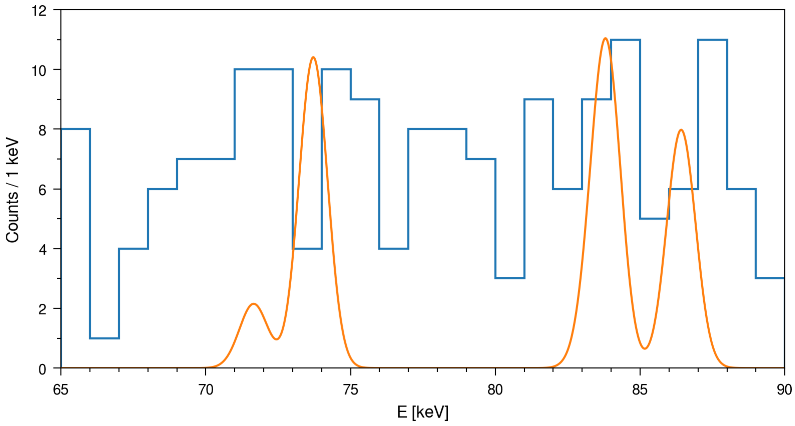

Figure 2: Spectrum acquired with the germanium detector in the VIP-Lead experiment, in about 70 days of data taking. The expected signal distribution is shown in orange with arbitrary normalization. Reproduced from [12].

As result, the κ-Poincaré model, in the Arzano-Marcianò [21] κ-Poincaré fields' quantization model, is ruled out as we obtain $\Lambda_1 > 4.2 \times 10^{21}$ Planck scales. The θ-Poincaré model can be excluded up to a fraction of the Planck scale, with $\Lambda_2 > 1.6 \times 10^{-1}$ Planck scales.

In particular, we performed the first measurement for the $k = 3$ case, excluding this scenario up to $\Lambda_3 > 5.6 \times 10^{-9}$ Planck scales. These results provide valuable experimental guidance towards future developments of possible models, including the triply special relativity framework.

4. Conclusions

The VIP collaboration is conducting high precision X-ray spectroscopy experiments at INFN's Gran Sasso Underground National Laboratory to search for PEP-violating atomic transitions, providing insights into the foundation of the modern quantum theory and of the physics beyond the Standard Model. The VIP-2 experiment is leading the collaboration's effort in the open system framework, aiming to improve the exclusion limit for PEP violation, and reaching $\beta^2/2 < 8.6\times10^{-31}$ with six months of data taking. The full dataset being analyzed, and the first results show a significant improvement in the exclusion limit. The VIP-3 experiment is designed to extend these investigations to heavier elements, and the experimental setup is under construction, aiming to start data acquisition in 2025.

The VIP-Lead effort is focused on the closed system scenario, where the PEP violation is searched in the lead atoms, within the context of Non-Commutative Quantum Gravity frameworks. We have significantly constrained the available parameter space for the κ-Poincaré, θ-Poincaré, and triply special relativity models, providing a pathway for future developments in quantum gravity.

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