Proceedings of the 4th Jagiellonian Symposium on Advances in Particle Physics and Medicine

High Sensitivity Pauli Exclusion Principle Tests by the VIP Experiment: Status and Perspectives

K. Piscicchia[a,b,*], S. Bartalucci[b], S. Bertolucci[c], M. Bazzi[b], G. Borghi[d], M. Bragadireanu[b,e], C. Capoccia[b], M. Cargnelli[f], A. Clozza[b], R. Del Grande[b,g], L. De Paolis[b], C. Fiorini[h], C. Guaraldo[b], M. Iliescu[b], M. Laubenstein[i], J. Marton[f], M. Miliucci[b], E. Milotti[j], F. Napolitano[b], A. Porcelli[b,f], A. Scordo[b], H. Shi[f], D.L. Sirghi[a,b,e], F. Sirghi[b,e], F. Sgaramella[b], N. Zorzi[d], J. Zmeskal[f] and C. Curceanu[b,e]

[a] *Centro Ricerche Enrico Fermi-Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Via Panisperna 89a, I-00184 Roma, Italy*
[b] *INFN, Laboratori Nazionali di Frascati, Via E. Fermi 54, I-00044 Frascati(RM), Italy*
[c] *Dipartimento di Fisica e Astronomia, University of Bologna and INFN-Sezione di Bologna, Via Irnerio 46, I-40126 Bologna, Italy*
[d] *Fondazione Bruno Kessler, Via Santa Croce 77, 38122 Trento, Italy*
[e] *Horia Hulubei National Institute of Physics and Nuclear Engineering, Str. Atomistilor No. 407, P.O. Box MG-6 Bucharest-Magurele, Romania*
[f] *Stefan Meyer Institute for Subatomic Physics, Kegelgasse 27, 1030 Wien, Austria*
[g] *Physik Department E62, Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany*
[h] *Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria and INFN Sezione di Milano, I-20133 Milano, Italy*
[i] *INFN, Laboratori Nazionali del Gran Sasso, Via G. Acitelli 22, I-67100 L'Aquila, Italy*
[j] *Dipartimento di Fisica, Universitá di Trieste and INFN-Sezione di Trieste, Via Valerio, 2, I-34127 Trieste, Italy*

Doi: 10.12693/APhysPolA.142.361 *e-mail: kristian.piscicchia@cref.it

The VIP Collaboration is performing high sensitivity tests of the Pauli exclusion principle for electrons in the extremely-low cosmic background environment of the Gran Sasso underground National Laboratory of INFN. In its open-systems configuration, the experiment checks the continuously renewed symmetry state of the conductive target, constantly supplied with electrons through a direct current. Consequently, VIP is operating the sole experiment challenging the spin–statistics connection in compliance with the Messiah–Greenberg superselection rule. The strongest bounds set by the VIP-2 experiment on the Pauli exclusion principle violation probability, by exploiting a copper target, will be reviewed. The future VIP-3 experiment will be presented, the aim of which is to map the Pauli exclusion principle violation probability as a function of the atomic number of the target under test.

topics: Pauli exclusion principle, X-rays spectroscopy, SDD detectors

1. Introduction

According to the Pauli exclusion principle (PEP), two identical fermions cannot simultaneously occupy the same quantum state [1]. PEP is deeply grounded in our microscopic description of Nature, explaining a wide spectrum of physical phenomena, ranging from the stability of atoms and nuclei [2] to superconductivity, and even to the structure of neutron stars [3]. Despite its simple formulation, PEP still lacks an intuitive explanation [4, 5], and a comprehensive demonstration requires a quantum field theory conceptualization, as outlined by Fierz [6] and then finally proven by Pauli himself [7]. In this context, the spin-statistics theorem showed that PEP arises from the anti-commutation rules of fermionic spinor fields and accounted for the existence of two classes of elementary particles (bosons and fermions) associated with states of identical particles which are necessarily either symmetric (for bosons) or antisymmetric (for fermions) with respect to their permutation.

Attempts to formulate theoretical models that violate the statistics of identical particles were pioneered by Fermi [8, 9], who discussed the implications of even a tiny non-identity of electrons. Gentile introduced intermediate statistics [10], while parastatistics was developed by Green [11, 12]. Ignatiev and Kuzmin presented a model involving the deformation of the standard Fermi oscillator [13–15], also discussed by Okun [16]. In this approach, a three level Fermi oscillator is considered, in which an additional level can be accessed with a probability of $\beta^2/2$. In this research field, β is still used to represent the amplitude of a PEP violating transition. Rahal and Campa investigated the consequences of small PEP violations on the thermodynamic properties of matter [17]. Greenberg and Mohapatra [18, 19] formulated a local quantum field theory embedding PEP violation, named *quon model* after the q parameter introduced in the model to deform the algebra

$$a_i a_j^\dagger - q a_j^\dagger a_i = \delta_{ij}. \tag{1}$$

The q parameter is related to the violation probability by the relation $\beta^2 = 1 + q$. We refer to [20] for a more detailed review.

The experimental investigation of an observable signature of a PEP violation, which is strongly demanded to constraint the free parameters of the models, is complicated by a simple but stringent condition that is common to all of the theoretical frameworks listed above, known as the Messiah–Greenberg (MG) superselection rule [21]. The rule states that transitions between states with different symmetry are forbidden. Therefore, a consistent test of these models requires, for instance, checking the newly formed symmetry state that follows the introduction of new fermions in a given system of identical fermions. We refer to this class of experiments as the *open quantum systems* spin-statistics tests. A prototype experiment of this class was performed by Ramberg and Snow [22], following the suggestion of Greenberg and Mohapatra [18].

The VIP Collaboration is performing high-precision open-systems tests of PEP for electrons at the Gran Sasso underground National Laboratory of INFN and has already improved (see [23]) the Ramberg and Snow result by a factor of 400. The strategy is to introduce new electrons in the copper target by means of a direct current (DC). The searched signature of a PEP violation is represented by an anomalous electronic transition from the $2p$ to the $1s$ level (K_α) in a copper atom when the fundamental level is already occupied by two electrons. The PEP violating transition would be shifted backwards by about 300 eV with respect to the standard line, as a consequence of the additional screening effect produced by the second electron occupying the fundamental level. The calculation of the Pauli-forbidden radiative-transition energies is performed using the numerical code MCDFGME [24]. This program solves the multiconfiguration Dirac–Fock equations self-consistently, taking into account relativistic effects (see [25] and references therein). The violating $K_{\alpha1}$ transition would correspond to 7746.73 eV (standard 8047.78 eV), and the violating $K_{\alpha2}$ transition would corresponds to 7728.92 eV (standard 8027.83 eV); the calculated values are affected by relative errors of the order of 10^{-6}. The status and results of the upgraded VIP-2 experiment, which aims to improve the VIP result by at least two orders of magnitude, are reviewed in Sect. 2.

In the short-term future, research on the MG allowed PEP violation demands a comparable sensitivity scan of the PEP violation probability as a function of the atomic number. To use the words of Okun [26]: "The special place enjoyed by the Pauli principle in modern theoretical physics does not mean that this principle does not require further and exhaustive experimental tests. On the contrary, it is specifically the fundamental nature of the Pauli principle which would make such tests, over the entire periodic table, of special interest". This is the scientific goal of the VIP-3 experiment. Section 3 is devoted to the description of the ongoing research and development (R&D) and preparation activities for the implementation of the VIP-3 setup, which will take over after VIP-2 once the data-taking is concluded (end of 2023/beginning of 2024).

2. The VIP-2 experiment

The goal of the VIP-2 experiment is to improve by at least two orders of magnitude the result obtained by VIP ($\beta^2/2 < 4.7 \times 10^{-29}$; X-ray spectra measured, used to extract the limit, are presented and extensively discussed in [23, 27]). This is being achieved by a major upgrade of the experimental setup and a refined scheme for the statistical interpretation of the data. An advanced model of current electrons propagation and interaction inside the target is also under development.

The main improvements of the experimental apparatus (see [25, 28] for a detailed description) consist in:

(i) replacement of the charged coupled devices for the X-rays detection with the state-of-the-art silicon drift detectors (SDDs) with a thickness of 450 μm characterized by higher energy resolution (190 eV (FWHM) at 8 keV), large geometrical acceptance and efficiency of 99% at 8 keV;

(ii) a more compact and thinner target, ensuring higher acceptance and efficiency;

(iii) a new target cooling system that allows an enhanced circulating current (with a peak value of 180 A with respect to the 40 A of VIP). After the exploratory data-taking run (2016–2017) [25, 28] using two arrays of 1×3 SDDs, the fully upgraded setup was completed (2018–2019) by mounting four arrays

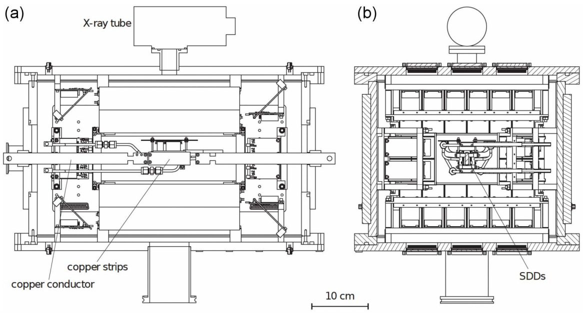

Fig. 1. The lateral (a) and front (b) sections of the vacuum chamber and the inner components of the VIP-2 apparatus.

of 2×4 SDD cells and the external passive shielding complex (an outer lead layer surrounding an internal copper layer) aimed to provide further suppression of environmental radiation from underground rocks.

The VIP-2 experiment has been operating in its final configuration since May 2019, alternating data-taking periods with the current on to the periods with the current off.

The VIP-2 target consists of a pair of copper strips, each 71 mm long, 20 mm high, and 25 μm thick, with an interposed cooling pad refrigerated via a closed chiller circuit (the design of the inner components of the VIP-2 setup is shown in Fig. 1). The SDD arrays — two for each external strip face — are cooled down to $-90°$C. In-situ calibration of detectors is performed by means of a Fe-55 radioactive source. The whole system (target, detectors, cooling, front-end electronics and calibration devices) is enclosed in a vacuum chamber kept at a pressure of 10^{-5} mbar.

The sensitivity of the VIP-2 experiment was demonstrated by a progressive approach of the $\beta^2/2$ limit to the foreseen goal [25, 28, 29]. The strongest bound on the PEP violation probability, consistent with the MG superselection rule (see [30]), was recently achieved by VIP-2, based on an analysis of data corresponding to about six months of experiment operation in its final configuration. Two analysis frameworks were followed, namely the Bayesian statistical model and the frequentist confidence levels (CL) approach, which share the same spectral shape description for the signal and the control spectra. It was found that the exclusion points are well consistent within one sigma (measured spectra, with and without the current circulating in the target, and a detailed discussion of the performed analyses are presented in [30]). The two approaches result in the following upper limits for the PEP violation probability for electrons in copper

$$\begin{aligned} &\beta^2/2 \leq 8.6 \times 10^{-31} \quad \text{(Bayesian)}, \\ &\beta^2/2 \leq 8.9 \times 10^{-31} \quad \text{(CL)}, \end{aligned} \tag{2}$$

when the propagation of electrons in the target is described using the electron diffusion model [22], i.e., the number of electron–atom interactions is obtained from the ratio of the target length and the electrons scattering length in copper.

According to the more realistic diffusion models [31, 32], on which we are recently working, the electron–atom interactions in copper occur over a characteristic time $\tau = 3.3 \times 10^{-17}$ s, therefore significantly increasing the number of independent PEP tests performed by each current electron, leading to the enhanced limits

$$\begin{aligned} &\beta^2/2 \leq 6.8 \times 10^{-43} \quad \text{(Bayesian)}, \\ &\beta^2/2 \leq 7.1 \times 10^{-43} \quad \text{(CL)}. \end{aligned} \tag{3}$$

3. The VIP-3, testing PEP over the periodic table

The main technical challenge to be faced when trying to test the PEP atomic transitions for metals characterized by a higher atomic number than copper, is the decrease of the quantum efficiency of SDD detectors as a function of increasing energy. To overcome this problem, our group at Laboratori Nazionali di Frascati (INFN, Italy), in collaboration with Fondazione Bruno Kessler (FBK, Italy) and Politecnico di Milano (PoliMi, Italy), is currently developing new cutting edge SDD detectors characterized by double thickness, with respect to the standard detectors used in the VIP-2 experiment (1 mm versus 0.45 mm). We have already demonstrated (see Fig. 2) that the quantum efficiency of the new SDDs, in the energy range 20–25 keV, is roughly double that of standard detectors, while the energy resolution remains constant. This will allow investigation of eventual PEP violation-induced deviations, from the standard K_α transitions in palladium, silver and tin. For example, in silver, the

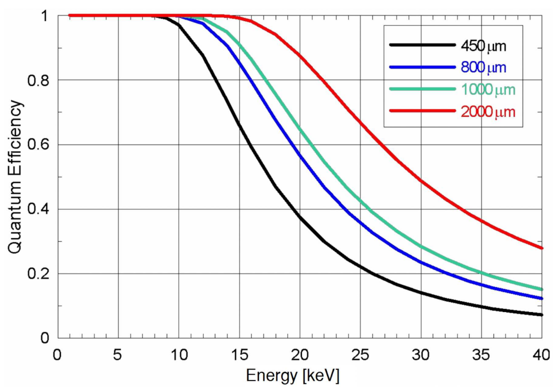

Fig. 2. The figure shows the quantum efficiency as a function of energy, for SDD devices of various thicknesses. The black curve corresponds to the detectors currently used in VIP-2, the green curve shows the efficiency achievable with the new 1 mm thick SDDs which we are presently developing for the VIP-3 experiment.

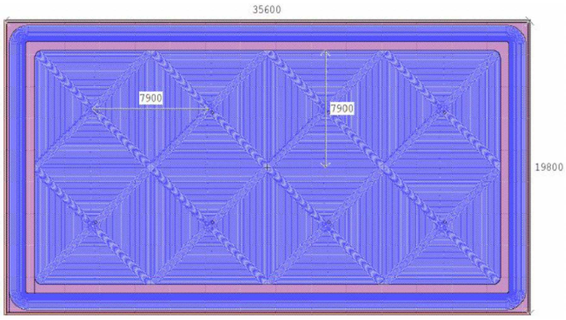

Fig. 3. The figure shows the layout of the main SDD array, which is produced for the VIP-3 experiment from the anode side.

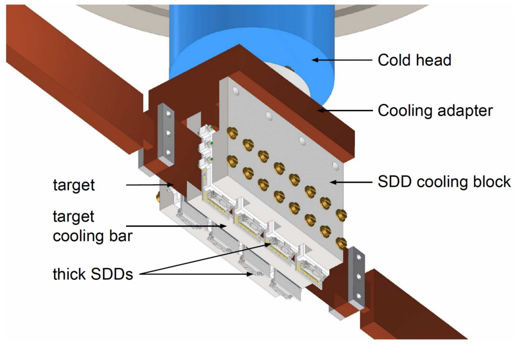

Fig. 4. Schematic representation of the inner configuration of the VIP-3 apparatus. The 8 SDD arrays facing the two target strips are shown, along with the target and the SDD detectors cooling system.

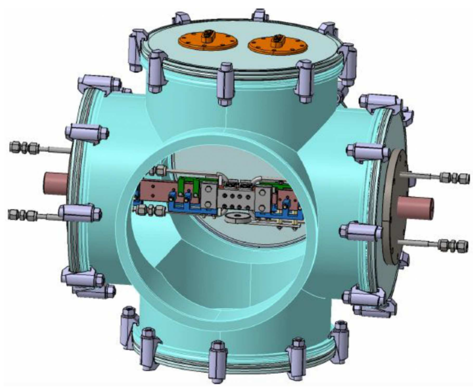

Fig. 5. Design of the vacuum chamber which is being optimized for the VIP-3 setup.

PEP violating $K_{\alpha 1}$ transition is shifted of 482.70 eV with respect to the standard line, and the corresponding shift for the $K_{\alpha 2}$ is 478.80 eV. Comparable shifts are found in palladium and tin. Production of the new SDD devices is presently ongoing and the finalization is previewed for the end of 2022. The new system is characterized by pixel dimensions of 7.9×7.9 mm^2, the width of the last ring has been extended in order to improve collection at the border of the active area. The total dimensions of the chip are 35.6×19.8 mm^2, which is about 2 mm wider than the previous chips. The geometry of the SDD arrays will consist of a 2×4 matrix, the anode side of which is shown in Fig. 3. Among the main improvements characterizing the new detector system, we want to mention the introduction of a layout solution on the window-side to reduce the charge-sharing effect. Moreover, the robustness of the bonding pads was enhanced.

We are currently finalizing Monte Carlo (MC) studies to optimize the setup design, in particular the targets (Pd, Ag, and Sn) geometry, the target-SDDs geometrical efficiency, the SDDs and target cooling systems efficiency, the groundings and cable lengths for noise reduction and electrical stability. The layout of the compact targets-SDD detectors system is shown in Fig. 4. The planned configuration will consist of 8 SDD arrays, facing two target strips, where the direct current will be circulated. With respect to the 4 SDD arrays presently arranged in the VIP-2 setup, VIP-3 will exploit a total of 64 SDD cells, for a double active area of about 41 cm^2, in order to increase the geometrical efficiency. A new thermal contact will be realized between the cold-finger and the SDD detectors, made of pure copper to minimize the natural copper radio-contamination. A new target cooling system made of pure copper will also be built. With respect to the steel thermal contact and cooling system currently used in VIP-2, the new copper structures will introduce further advantage. Copper is characterized by almost one order of magnitude higher thermal conductivity than steel. This will reduce the detectors working temperature (improving the energy and timing resolution) and also increase the applicable maximum current circulating in the target (from the 180 A peak current of VIP-2 up to 400 A). The introduced improvements compensate the quantum efficiency reduction, from 8 to 25 keV, thus keeping the sensitivity of the experiment at least constant.

The readout electronics, dedicated to the new SDD technology, is also under study. The front-end electronics must satisfy higher performances in terms of gain, stability and linearity.

The design of the vacuum chamber (shown in Fig. 5) is being completed and optimized to arrange the new compact SDD detectors, front-end electronics and cooling system. The increased number of active channels requires the realization of a new cold head to satisfy the higher power request, and new vacuum flange connectors are to be realized. Moreover, the vacuum-tight electrical feedthrough will be improved in terms of electrical stability and thermal dissipation, in order to allow safe operation up to 400 A circulating current.

The external shielding complex, surrounding the vacuum chamber will be also improved by adding to the lead and copper layers a further inner polyethylene tier, which will serve for neutrons suppression.

4. Conclusions

We reviewed the status and results of the VIP-2 experiment at the Gran Sasso underground National Laboratory (LNGS) of INFN, which represents the highest sensitivity test of the Pauli exclusion principle for electrons, fulfilling the Messiah–Greenberg superselection rule. The analyses of data corresponding to about six months of operation, of the VIP-2 experiment in its final configuration, allow to set the following constraints on the Pauli exclusion principle violation probability

$$\begin{aligned} \beta^2/2 &\leq 8.6 \times 10^{-31} \quad \text{(Bayesian)}, \\ \beta^2/2 &\leq 8.9 \times 10^{-31} \quad \text{(CL)}, \end{aligned} \tag{4}$$

based on two independent Bayesian and frequentist CLs analyses, respectively, and assuming the electrons propagation to be described by a simple electron diffusion model. If a more realistic diffusion random walk model is accounted for, the following limits are obtained

$$\begin{aligned} \beta^2/2 &\leq 6.8 \times 10^{-43} \quad \text{(Bayesian)}, \\ \beta^2/2 &\leq 7.1 \times 10^{-43} \quad \text{(CL)}. \end{aligned} \tag{5}$$

The R&D and preparation activities of the future VIP-3 experiment, the aim of which is to perform a comparable sensitivity scan of $\beta^2/2$ as a function of the atomic number, were described in detail. New cutting-edge SDD devices dedicated to VIP-3, characterized by more than double thickness with respect to the currently available technology, are at an advanced state of production. Optimization and design of the experimental apparatus are under finalization. The installation of the experiment at LNGS is expected for the end of 2023/beginning of 2024.

Acknowledgments

This publication was made possible through the support of Grant 62099 from the John Templeton Foundation. The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of the John Templeton Foundation. We acknowledge support from the Foundational Questions Institute and Fetzer Franklin Fund, a donor advised fund of Silicon Valley Community Foundation (Grants No. FQXi-RFP-CPW-2008 and FQXi-MGB-2011), and from the H2020 FET TEQ (Grant No. 766900) and INFN (VIP). We acknowledge the LNGS (INFN) for the excellent working conditions and the constant support. 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). K.P. acknowledges support from the Centro Ricerche Enrico Fermi-Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi" (Open Problems in Quantum Mechanics project).

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