The key role of the Silicon Drift Detectors in testing the Pauli Exclusion Principle for electrons: the VIP-2 experiment

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Abstract. The VIP experiment performed an accurate investigation of the Pauli Exclusion Principle for electrons. The apparatus was installed in the Gran Sasso Laboratories of the National Institute of Nuclear Physic in Italy, an underground environment with an extremely low cosmic background. The aim of the experiment was to test the Pauli Exclusion Principle for electrons in a copper target circulated by a Direct Current (DC) current, searching for X-rays emission due to an atomic transition forbidden by Pauli exclusion principle, from the L shell to the K shell of copper when the K shell is already occupied by two electrons. VIP set an upper limit on the Pauli exclusion principle violation probability $\frac{1}{2}\beta^2 < 4.7 \times 10^{-29}$. The goal of the upgraded VIP-2 experiment, presently in data taking at Gran Sasso Laboratories, is to improve this limit by two orders of magnitude. The VIP-2 experimental apparatus, in which the Silicon Drift Detectors have the key role of X-ray detectors, and preliminary results are presented.

1. Introduction

In 1945 Wolfgang Ernst Pauli was awarded the Nobel Prize in physics for the formulation of the Pauli Exclusion Principle (PEP). Initially proposed for electrons, it was later extended to all the fermions.

The PEP is a direct implication of the spin-statistic theorem and it states that two identical fermions cannot occupy the same quantum state.

This principle represents a fundamental cornerstone of the Quantum Physics and it's the basis for the explanation of numerous phenomena in various fields of physics, ranging from the chemical properties of elements in the periodic table to the stability of neutron stars.

In his Nobel lecture Pauli said:

"Already in my original paper I stressed the circumstance that I was unable to give a logical reason for the exclusion principle or to deduce it from more general assumption. I had the feeling and I still have it today, that this is a deficiency. The impression that the shadow of some incompleteness fell here on the bright light of success of the new quantum mechanics seems to me unavoidable" [1].

It can be demonstrated within the Quantum Field Theory (QFT) that the quantum states of identical bosons are symmetric with respect to their permutation and the quantum states of identical fermions are antisymmetric with respect to their permutation. In addition, the Messiah-Greenberg (MG) superselection rule [2] forbids transitions between different symmetry states in a given system of identical particles. Hence, a violation of the PEP, whose probability is usually quantified through the $\frac{\beta^2}{2}$ parameter [3, 4], would imply the existence of particles that follow a different statistics than fermionic or bosonic and, therefore, it would set the basis for a new physics beyond the Standard Model.

The VIP collaboration is testing the validity of PEP with an experimental technique, pioneered by Ramberg and Snow (see Ref. [5]), based on circulating a high DC in a copper conductor in order to allow to a large number of newly-injected conduction electrons to interact with copper atoms. New electrons are introduced in the copper target in order to search for signal of non-Paulian atomic transitions in a system which fulfills the MG superselection rule.

The PEP-violating K_α transition is a $2p \rightarrow 1s$ transition with the $1s$ level already occupied by two electrons. The energy of the transition is shifted of about 300 eV with respect to the standard K_α line due to the shielding effect of the two electrons in the ground state, and is then distinguishable in precision spectroscopic measurements.

A reference spectrum is acquired with current off in order to describe the background.

More detailed information about the experimental method can be found in references [6, 7, 8].

The goal of this work is to present the fundamental role of the Silicon Drift Detector (SDD) in the upgraded VIP-2 experimental apparatus (see Refs. [9, 10]). VIP-2 succeeded, in the first months of data taking, to improve the upper limit on the probability of PEP violation for electrons in copper set by VIP in four years of data taking.

2. The VIP-2 experiment: improving VIP using SDDs for the X-ray detection

The VIP experiment set the best upper limit on the PEP violation probability for electrons $\frac{\beta^2}{2} < 4.7 \times 10^{-29}$ [7] exploiting the extremely low cosmic background environment of the LNGS. The data taking at LNGS started in the spring of 2006 and ended in 2010.

The X-ray detector used in VIP was the Charge Coupled Device (CCD) type 55 produced by English Electric Valve, a solid state detector with a pixeled structure and a Full Width at Half Maximum (FWHM) at 8 keV of about 320 eV. The active area of each detector was 7.25 cm^2 and the efficiency was ~48% for a 7.7 KeV X-ray.

The VIP-2 experiment is being realized to test more precisely the possible violation of PEP for electrons in copper, with the aim to improve the VIP upper limit by about 2 orders of magnitude. In order to achieve this result, substantial changes have been made to the

experimental apparatus. Among them, a crucial role is played by the choice of Silicon Drift Detectors (SDDs) as X-ray detectors.

The SDD is a solid state detector whose working principle is based on sideward depletion, which was first introduced in [11]. This detector is built taking a cylindrical n-type silicon wafer on which are implanted, on the flat surface, circular p^+ silicon contacts, used to apply an increasing reverse bias in order to fully deplete the wafer.

On the opposite side of concentric contacts a radiation entrance window is positioned. It consists of homogeneous shallow junction to give homogeneous sensitivity over the whole surface. If a charge particle or a photon hits the silicon wafer, electron-hole pairs are generated. The free electrons move, following the lower potential due to the concentric electrodes, to the anode consisting of a ring close to the middle of the wafer. The amount of charge collected by the anode is proportional to the energy of the radiation.

The anode of the SDD has a capacitance of approximatively 100 fF, decreasing the noise, which is proportional to the capacitance and also allowing a shaping time of only about 500 ns, which means the possibility to work at high counter rates (up to 5 kHz). As first stage of readout electronics a Field Effect Transitor (FET) has been integrated in the detector.

A schematic drawing of a SDD used in VIP-2 is shown in Fig. 1. More details can be found in [12, 13, 14].
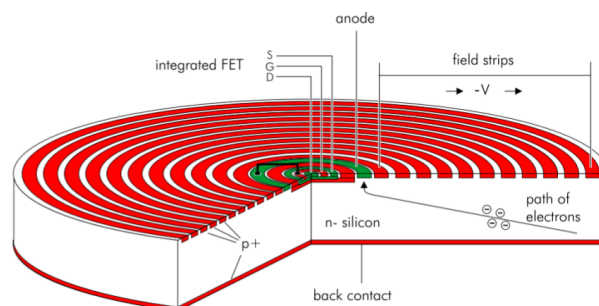

Figure 1. Scheme of a Silicon Drift Detector used in VIP-2

The VIP-2 new apparatus is presently taking data at LNGS. The target is composed of 2 strips with length of 71 mm, height of 20 mm and thickness of 25 µm and circulated by a DC current of 100 A.

The SDDs employed in this setup are two arrays 2×8 for a total of 32 SDDs, positioned on each side of the target. Each detector cell has an active area of 0.64 cm^2 and a thickness of 450 µm, which ensures an efficiency of about 99 % for 8 keV X-rays. The SDDs are cooled with a liquid argon circulating system at a temperature of about 150 K to achieve a resolution of 190 eV FWHM for the K_α copper transition line ($\sim$8 keV).

A cooling pad (cooled down by a closed chiller circuit) is placed in between the strips in order to avoid the temperature rise due to the heat dissipation in copper. When the 100 A current is circulating in the target, the temperature of both strips increase by about 10 °C, inducing a raise in the SDDs of about 1 K, which does not affect the energy response of the device [15].

An energy Region of Interest (ROI) of 200 eV, from 7648 eV to 7848 eV, is defined to look for PEP violating events, based on the SDDs energy resolution and centred on the energy of the PEP violating transition (estimated value of the PEP violating K_α transition is 7746.73 eV [10, 16]). In order to obtain the number of candidate violating PEP events in the ROI, the reference (normalised) spectrum with current off is subtracted from the spectrum collected with current on.

The SDDs of VIP-2 have a timing resolution of about 400 ns. This feature of the detector has

allowed the implementation of a veto system composed by 32 plastic scintillators, each of size
$40\,\text{mm} \times 32\,\text{mm} \times 250\,\text{mm}$ and read from both sides by silicon photomultipliers, which cover 90%
of the solid angle for the acceptance of the SDDs.
The veto system works as an active shielding, reducing the background in the ROI.
The entire apparatus is placed inside a vacuum chamber. The pressure is 10^{-5} mbar to allow
the cooling of SDDs.
A schematic view of the VIP-2 apparatus is shown in Fig. 2.
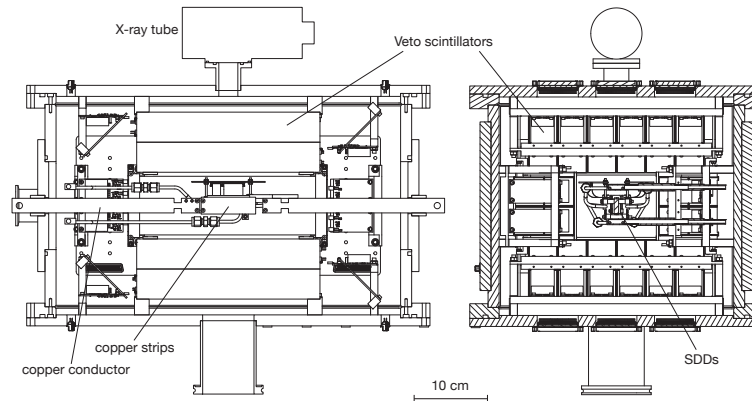
Figure 2. Schematic side views of the core components of the VIP-2 apparatus in which the
copper strips of target, the SDDs and the Veto scintillators are highlighted.

A passive shielding has been installed in November 2018 with the aim of further reduce the
background. It is composed of two layers, the internal made of copper and the external made
of lead.

3. Preliminary result and perspectives
A preliminary limit on $\frac{\beta^2}{2}$ can be obtained from the spectra collected in about two months of
data taking during 2018.
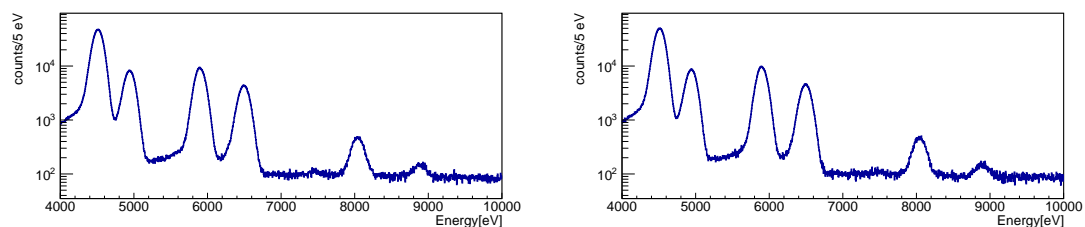The collected spectra are shown in Fig. 3.

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.

In analogy to the analyses performed in [5, 7] the statistical significance of an excess of events
in the ROI region is evaluated. From the spectra in Fig. 3 the number of possible detected events

violating PEP N_X is calculated as the difference between the measured counts in the current on (N_X^C) and current off (N_X^B) spectra, looking in the ROI energy interval estimated for an X-ray PEP-forbidden transition:

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

Considering the statistical error of N_X and using a three sigma upper bound, the number of possible PEP violating events is $\Delta N_X = 3 \cdot 90 = 270$ to give a Confidence Level (C.L.) of 99.7%. A new preliminary upper limit for PEP violation probability can be calculated with the following formula:

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

where $N_{\text{new}} = (1/e) \int_{\Delta t} I(t)dt$ is the number of current electrons injected in the copper target during the acquisition time period (with current) Δt, the factor 1/10 accounts for the capture probability (per electron-atom scattering) into the $2p$ state [17], $N_{\text{int}} = D/\mu$ 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, the detection efficiency ϵ is about 4% (factor obtained by means of a Monte Carlo simulation). 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, using the three sigma upper bound to give a 99.7% C.L., the following upper limit is obtained for the PEP violation probability:

$$\frac{\beta^2}{2} \leq 1.6 \times 10^{-29} \tag{2}$$

This value represents an improvement by a factor of approximately 3 compared to the result of the VIP experiment obtained in about four years of data taking.
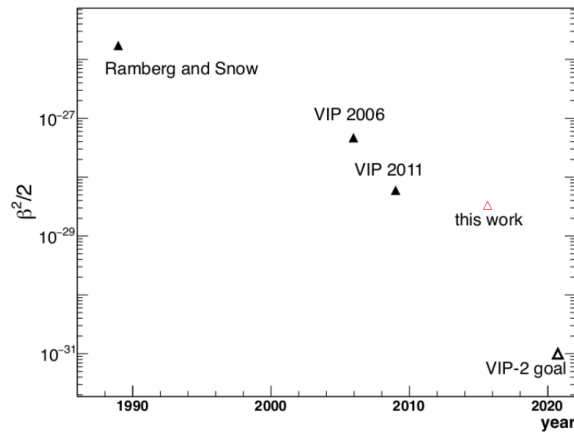

Figure 4. All the past results from PEP violation tests for electrons with a copper conductor, together with the result from this work and the goal of VIP-2 experiment. Note that the result of this work comes from two months of data taking, and it is already compatible with theVIP result from three years of operation

In Fig. 4 all the past experimental results of the PEP violation tests for electrons with a copper conductor are shown, together with the result presented in this work.

Presently, the VIP-2 setup is in data taking at LNGS, with the aim of reaching an upper limit on PEP violation for electrons of 5×10^{-31}, or, alternatively, to discover signals of the violation. The use of SDDs as X-ray detectors will be essential for achieving the intended goal of VIP2, as has already been the case for the new upper limit presented in this document.

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