Detector Setup of the VIP2 Underground Experiment at LNGS

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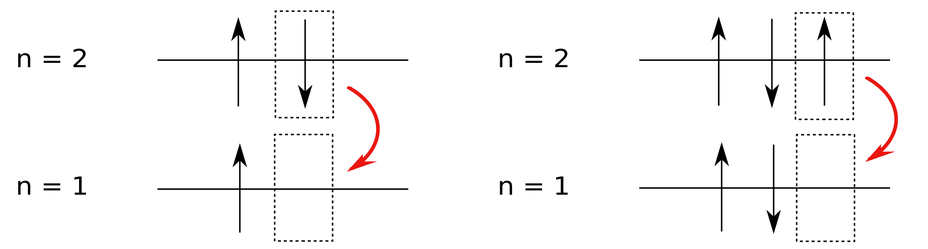
Introduction

In 1925 Wolfgang Pauli formulated the **Pauli Exclusion Principle (PEP)** explaining the shell structure of atoms. It turned out that this principle is valid not only for electrons - it is valid for all **fermions**, i. e. particles with half integer spin. In spite of the overwhelming success of the PEP in explaining many features of nature, a loophole-free proof cannot be given up to now.

A small violation of the PEP is qualitatively described by the parameter β, which was introduced by Ignatiev and Kuzmin [1]. The creation operator a^+ acting on the vacuum state $|0\rangle$ creates a state filled with one electron $|1\rangle$. The same creation operator acting on the state $|1\rangle$ creates a state of the form $\beta|2\rangle$, with the state $|2\rangle$ being a Pauli violating state with double occupation. The parameter β is very small and for $\beta = 0$ one arrives at Fermi-Dirac statistics.

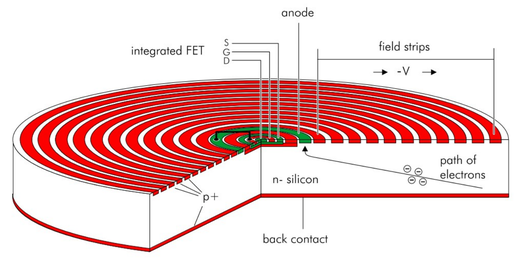


An allowed X-ray transition is displayed on the left. The VIP2 experiment is searching for the Pauli forbidden 2p → 1s transitions, which have lower transition energy compared to the normal transition due to the additional shielding of the second electron in the ground state (right).

The method to test the PEP used in VIP and VIP2 is similar to that of Ramberg and Snow [2]. By circulating an electric current **fresh electrons** are inserted into a Cu strip. They form new quantum states with atoms of the conductor. These quantum states have a probability of $\frac{\beta^2}{2}$ to be non-Paulian. The electron then cascades to the 1s state and thereby emits photons from non-Paulian transitions, which are detected. **Silicon Drift Detectors** are used as X-ray detectors. The number of possible photons from these transitions, which are identified by their energy, is used to set an upper limit for the probability for a violation of the PEP.

X-Ray Detectors

Silicon Drift Detectors are semiconductor detectors ideally suited for X-ray detection. Free electrons generated by incident radiation drift to the anode due to an applied electric field. From the number of electrons at the anode, the energy of the radiation can be inferred.



Schematic drawing of a Silicon Drift Detector.

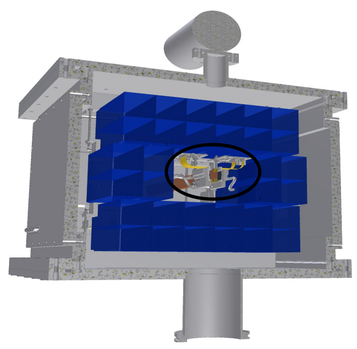
Silicon Drift Detectors represent an upgrade with respect to the Charge-Coupled Devices (CCD), which were used in the predecessor experiment VIP:

	Charge-Coupled Devices	Silicon Drift Detectors
Depletion Depth	50 µm	450 µm
Quantum Efficiency	48 %	99 %
Time Resolution	Several seconds	400 ns @ 100 K
Energy Resolution @ 8 keV	380 eV (FWHM)	190 eV (FWHM)
Detection Probability	2.1 %	1.82 %

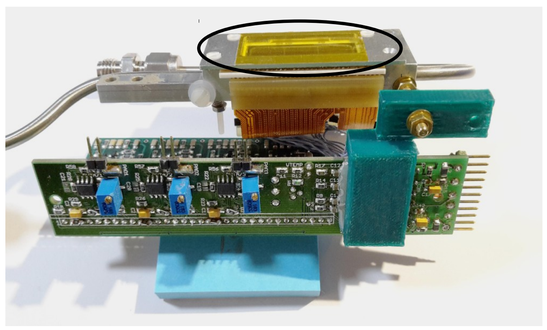
The improvements of SDDs are on the one hand due to their larger depletion depth, which leads to a higher detection efficiency of possible X-rays from PEP-violating transitions. On the other hand, the improved time resolution enables the use of an **active shielding** against external radiation. For this purpose, 32 scintillator bars read out by 2 silicon photomultipliers each are installed around the SDDs. Their veto signal helps to reduce the background.

The VIP2 Setup

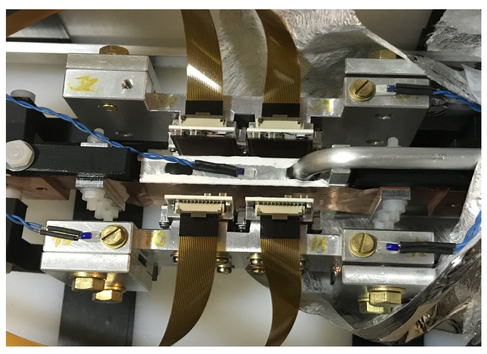
The VIP2 setup contains the Silicon Drift Detectors working as X-ray detectors. They are mounted close to a copper target, through which the high current flows. Target and detectors are surrounded by scintillators used as active shielding.



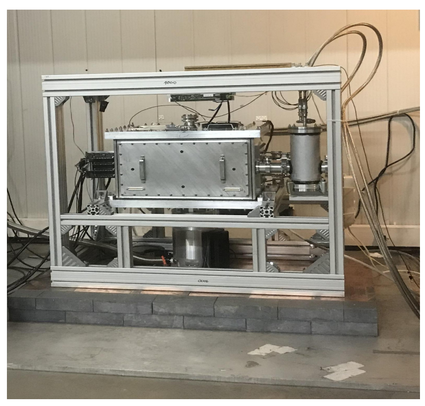
A render of the VIP2 setup with scintillators (blue) and Cu target and SDDs (marked in black).



The Silicon Drift Detectors used previously for VIP2 (marked in black) with cooling lines and preamplifier board.



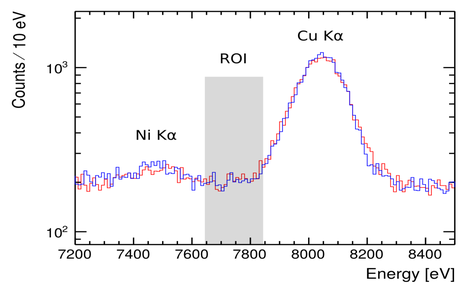
The new Silicon Drift Detectors mounted close to the Cu target in the setup, with readout cables and water cooling to counteract the heating due to the high current.



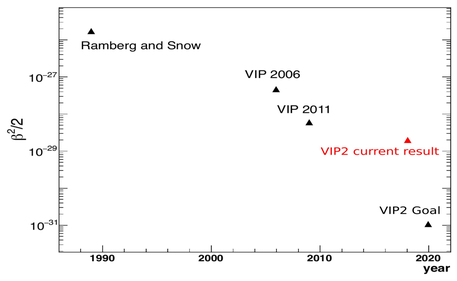
The vacuum chamber of VIP2 at LNGS, which contains the Cu target as well as the newly installed Silicon Drift Detectors.

Preliminary Results and Outlook

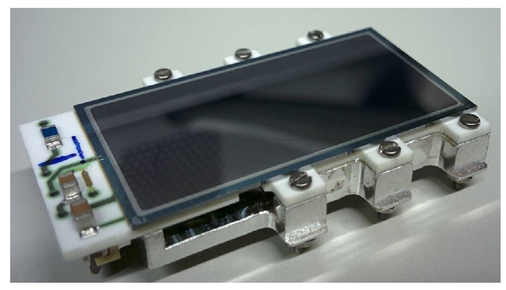
The VIP2 experiment has taken over 180 days of data in the Gran Sasso underground laboratory (LNGS). With these data, the Pauli Exclusion Principle could be tested with unprecedented precision.



Comparison of data taken with and without current at LNGS. The region of interest where the PEP violating transition is expected is marked in gray. The data corresponds to around 163 days.



The results of the VIP experiment, compared to the limit we can set with the data taken by the VIP2 experiment. The envisioned final result after the full data taking time is shown including a planned upgrade [2].



SDDs recently mounted in the VIP2 setup, which have a larger active are and enable easier cooling due to a higher working temperature.

With the data taken at LNGS, a new upper limit for the probability for a violation of the PEP can be calculated [3]:

$$\frac{\beta^2}{2} \leq 1.87 \times 10^{-29}$$

With planned improvements (e.g. lead shielding, new detectors), the goal of setting a new upper limit for the violation of the PEP to ~10^{-31} will be reached after 3 years of data taking or else a violation of the PEP will be discovered.

References:
[1] A.Yu. Ignatiev and V.A. Kuzmin, Yad. Fiz. 46, 786(1987)
[2] C. Curceanu et al. (VIP Collaboration), Entropy 19 (7), 300 (2017)
[3] A. Pichler, PhD Thesis, 2018

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