VIP 2: Experimental tests of the Pauli Exclusion Principle for electrons

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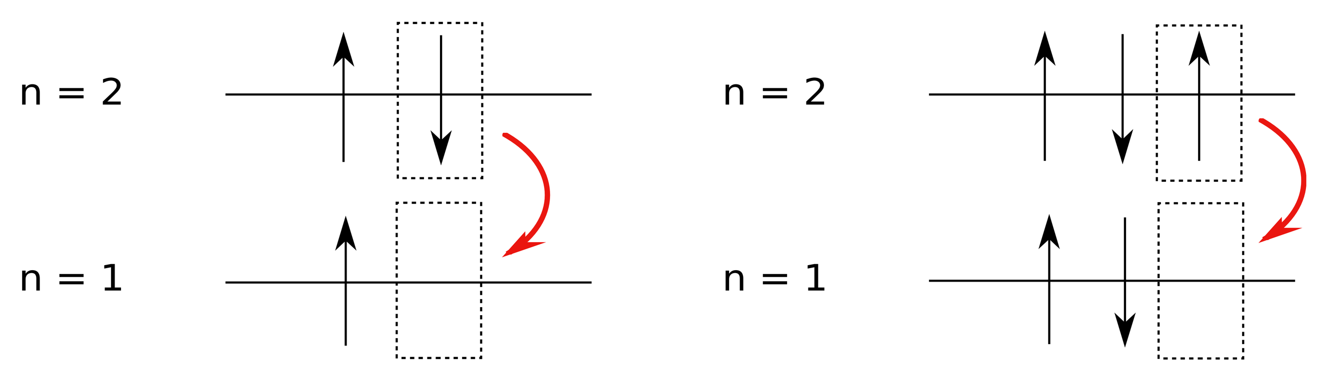
Introduction

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 simple explanation 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 can have Fermi-Dirac statistics again.



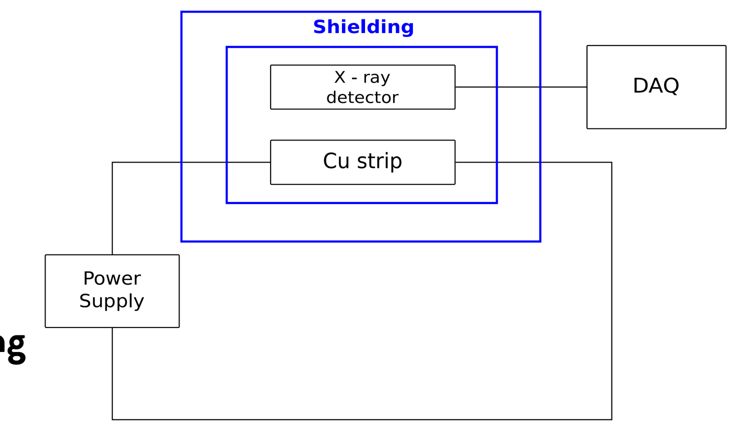
An allowed X-ray transition is displayed on the left. The VIP experiment is searching for the Pauli forbidden $2p \rightarrow 1s$ transitions, which have lower transition energy due to the additional shielding of the second electron in the ground state (right).

Year	Method	Upper limit ($\beta^2/2$)	Ref
1954	K capture	10^{-2}	Goldhaber and Scharff-Goldhaber
1989	spectroscopy	10^{-7}	Greenberg and Mohapatra
1990	anomalous X-rays	1.7×10^{-26}	Ramberg and Snow
2006	anomalous X-rays	4.5×10^{-28}	Bartalucci et. al

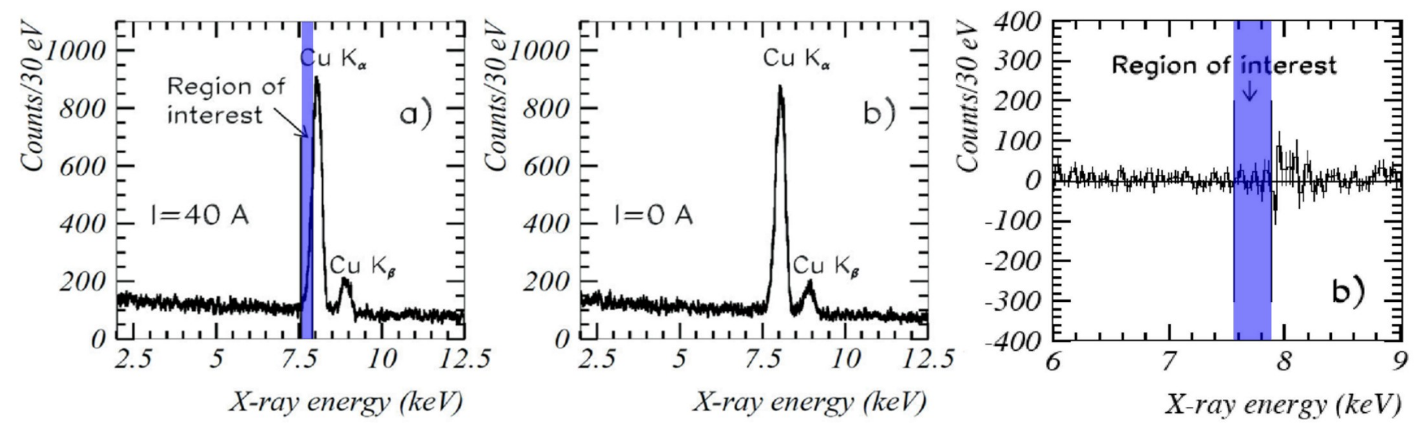
History of tests of the Pauli Exclusion Principle in the electron sector.

Experimental method of VIP

The PEP testing method used in VIP is similar to that of Ramberg and Snow [2]. The experiment is designed to detect anomalous - Pauli forbidden - X-ray transitions in copper. By circulating an electric current **fresh electrons** are probing the validity of the PEP dynamically. The scheme is shown on the right.



Scheme of the experiment for the detection of Pauli forbidden transitions.



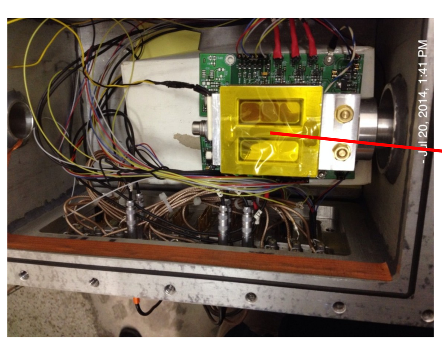
X-ray spectrum measured with circulating current (left), without current (middle) and the residual plot. The region of interest where Pauli violating Kα transitions are expected is marked in blue.

In the figure above X-ray energy spectra measured at LNF with and without circulating current are shown. In the region of interest about 300 eV below the Cu Kα line an excess of detected photons is expected in the spectrum with current if PEP is violated. This excess would originate from transitions, in which 2 electrons in the n = 1 shell shield the potential of the nucleus and diminish the energy of the Kα transition (see also plot in the upper left panel). After subtracting the spectrum without current from the spectrum with current, the residual spectrum shows no significant structure and a number of -21 ± 73 events were found in the region of the Pauli-forbidden K-transition. It was thus possible to determine an upper bound for the probability of the violation of the Pauli principle of [3]:

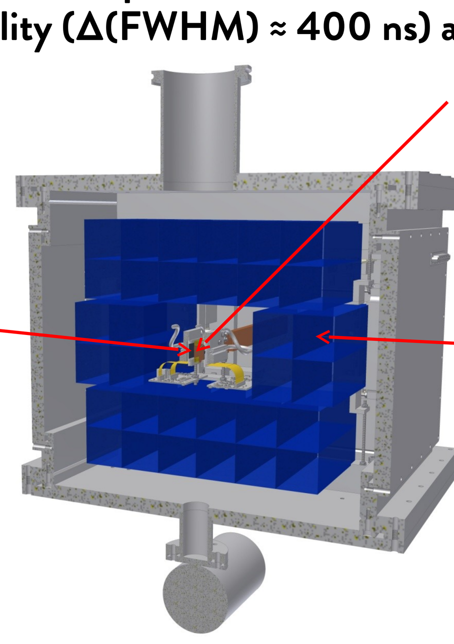
$$\frac{\beta^2}{2} \leq 4.5 \times 10^{-28}$$

The VIP 2 setup

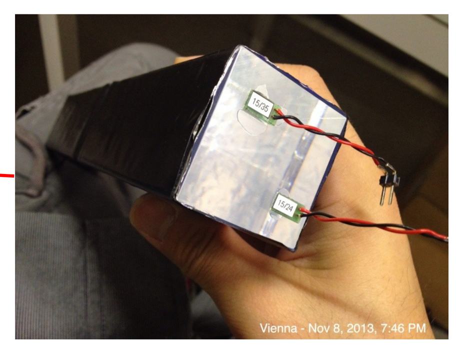
A major improvement of the VIP 2 setup compared to the VIP setup are the **Silicon Drift Detectors (SDDs)**, which are used as X-ray detectors. Their energy resolution (FWHM) is around 150 eV for the Mn Kα line compared to around 320 eV for the CCDs used for VIP. They also provide timing capability (Δ(FWHM) ≈ 400 ns) and a large detection area (100 mm²).



2 x 3 SDD array with preamplifier boards.

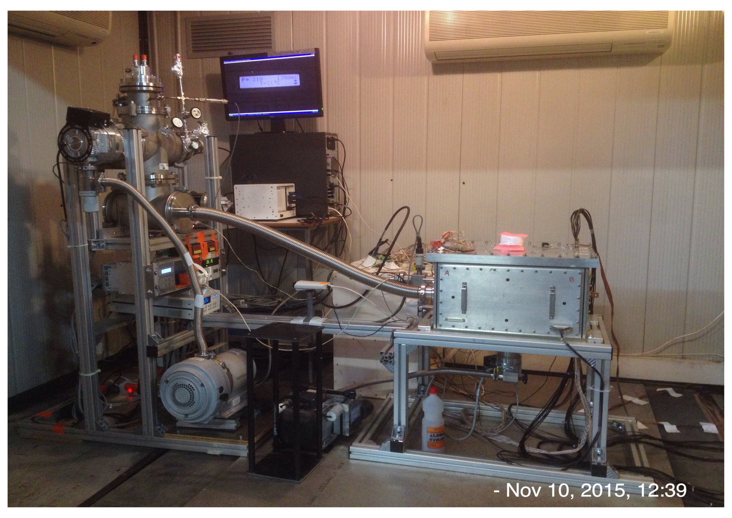


VIP 2 vacuum chamber.



Scintillator bar with SiPm readout.

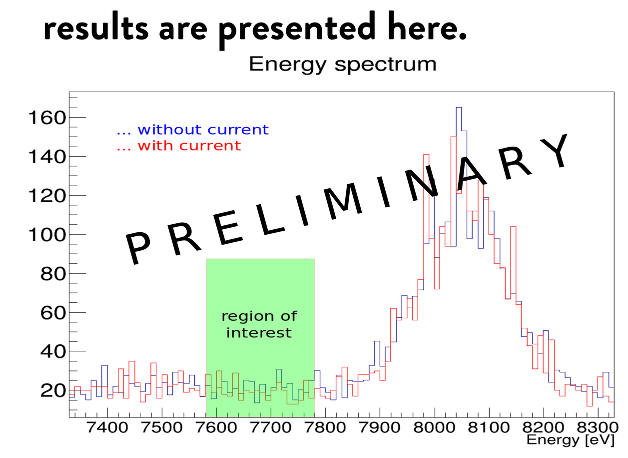
The use of X-ray detectors with timing capability enables the implementation of **active shielding**. For this purpose, scintillator bars read out by silicon photomultipliers are installed in the setup. These scintillators are used to give a veto signal. The resulting reduction of background is essential for improving the sensitivity and to reach the goal of further improvement of the PEP violation limit. Further reduction of background is achieved by continuing the data taking in the low background environment of the underground laboratory at Gran Sasso (LNGS).



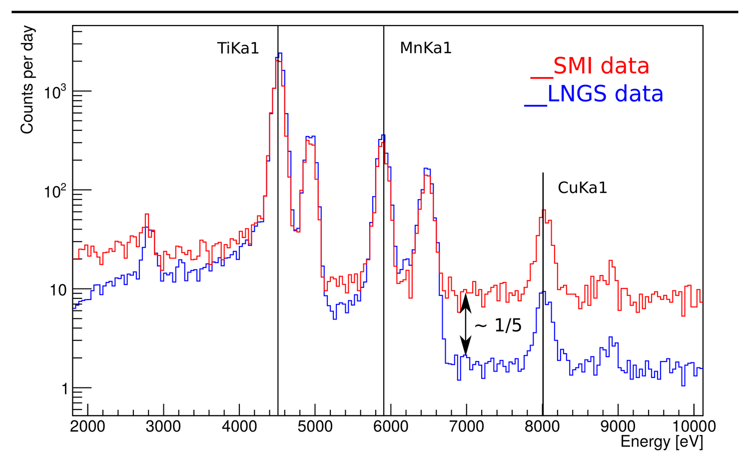
The vacuum chamber of VIP 2 at LNGS (right), which contains the Cu target and the detectors. The cryogenics needed to cool the SDDs is also visible (left).

Data taking and analysis

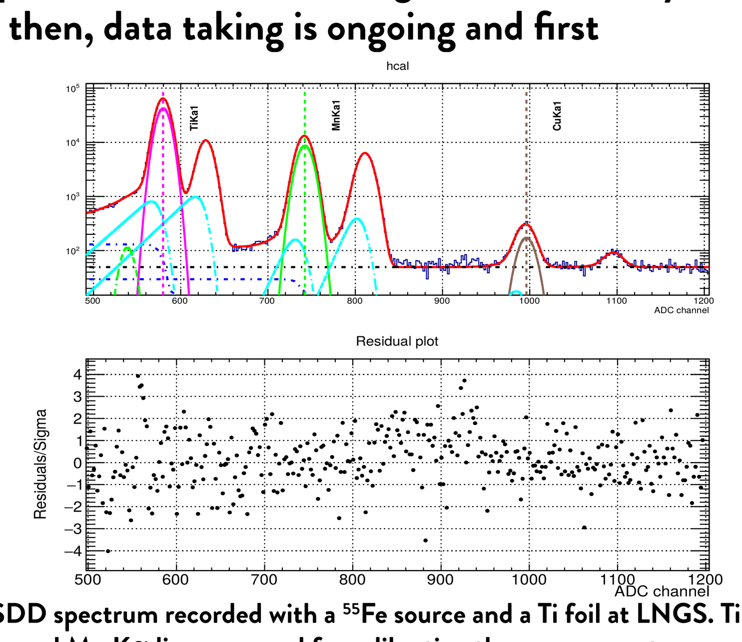
After around 4 months of data taking and thorough tests in the laboratory of Stefan Meyer Institute (SMI) in Vienna, the VIP 2 setup was taken to the underground laboratory of Gran Sasso (LNGS) in November 2015. Since then, data taking is ongoing and first results are presented here.



Comparison of data taken with and without current at SMI. The region of interest where the PEP violating transition is expected is marked in green.



Energy spectra taken at SMI and at LNGS. The surrounding mountain at LNGS reduces the background by a factor of ~ 5.



SDD spectrum recorded with a ^{55}Fe source and a Ti foil at LNGS. Ti and Mn Kα lines are used for calibrating the energy spectrum. Residuals compared to the fit are also shown.

The additional shielding of the surrounding mountain at the underground laboratory of LNGS reduces the background in the region of interest by a factor of ~5. The calculation of the parameter $\frac{\beta^2}{2}$ from the data taken at SMI and at LNGS is ongoing. With coming improvements (e.g. lead shielding), 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] E. Ramberg and G.A. Snow, Phys. Lett. B238, 438–441(1990)
[3] S. Bartalucci et al. (VIP Collaboration) Phys. Lett. B 641(2006)

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