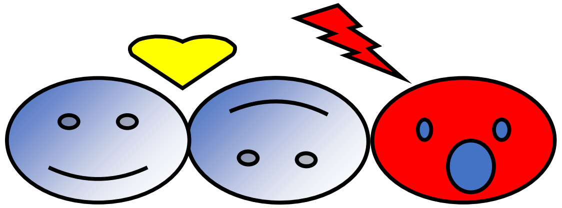
Experimental search for the Pauli Exclusion Principle violation:

The VIP-2 Experiment



LUCA DE PAOLIS

for the VIP2 Collaboration, LNF-INFN

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Laboratori Nazionali del Gran Sasso

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1. How it is possible to investigate the PEP with VIP-2

In Quantum Mechanics the PEP can be formalized starting from two fundamental principles:

1) All states, including those related to identical particles, are described in terms of wave functions

2) Bosonic and fermionic states have a different behavior in relation to the application of the exchange transformation (permutation) of identical particles: the former are symmetrical and the latter are anti-symmetrical

This superselection rule "does not appear as a necessary feature of the quantum-mechanical description of nature".

Messiah A.M.L. and Greenberg O.W.; *Physics Review* 1964, 136, B248.

1. How it is possible to investigate the PEP with VIP-2

States of mixed symmetry could, therefore, in principle, exist → Possible existence of particle states that follow a different statistic than the fermionic or bosonic one.

O. Greenberg, one of the pioneers of parastatistic studies, says that a possible violation of the PEP could be due to:

"Possible external motivations for violation of statistics include: (a) violation of CPT, (b) violation of locality, (c) violation of Lorentz invariance, (d) extra space dimensions, (e) discrete space and/or time and (f) noncommutative spacetime….".

O.W. Greenberg: AIP Conf.Proc.545:113-127,2004

1. How it is possible to investigate the PEP with VIP-2

The experimental method of VIP-2 is based on the introduction of "new" electrons in a copper bar by applying an electric current.

A small violation of PEP can be described in Quantum Mechanics as proposed by Greenberg in

O.W. Greenberg, Nucl. Phys. B (Proc. Suppl.)6, 83–89(1989):

Whenever an electron is captured by an atom, a new state is formed that can have a certain probability of being a mixed symmetry state. This state is highly excited and from its decay one could observe a possible transition prohibited by the PEP.

1. How it is possible to investigate the PEP with VIP2

Experimental goal: Search for X-rays from PEP violating transitions

Energy transition Kα allowed: **8.05 keV in Cu**

PEP forbidden Kα energy transition: **~ 7.74 keV in Cu**

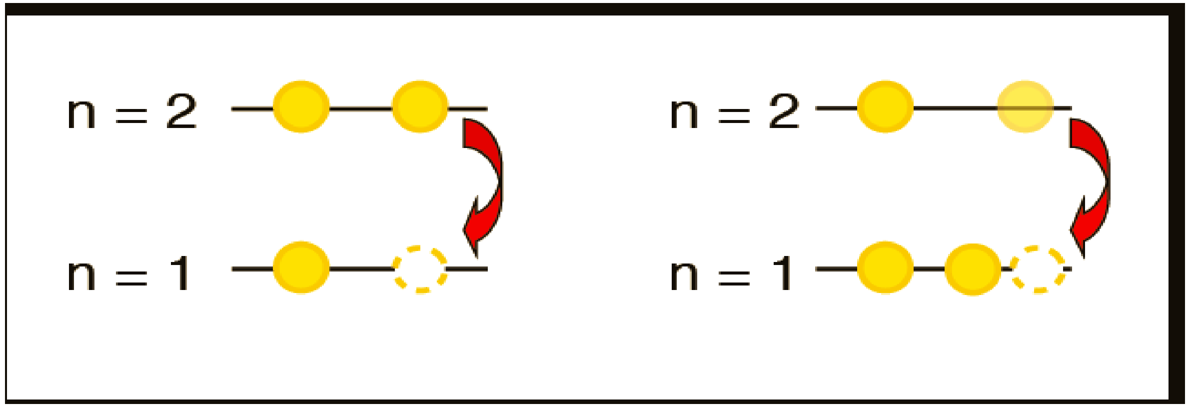
C. Curceanu, L. De Paolis et al., "Evaluation of the X-ray transition energy for the Pauli-principle-violating atomic transitions in several elements by using Dirac-Fock method", 2013, INFN-13-21/LNF.

MULTICONFIGURATIONAL DIRAC-FOCK METHOD

Software for muon atoms adapted to non-antisymmetric electrons

Parameter optimization through a self-consistent process

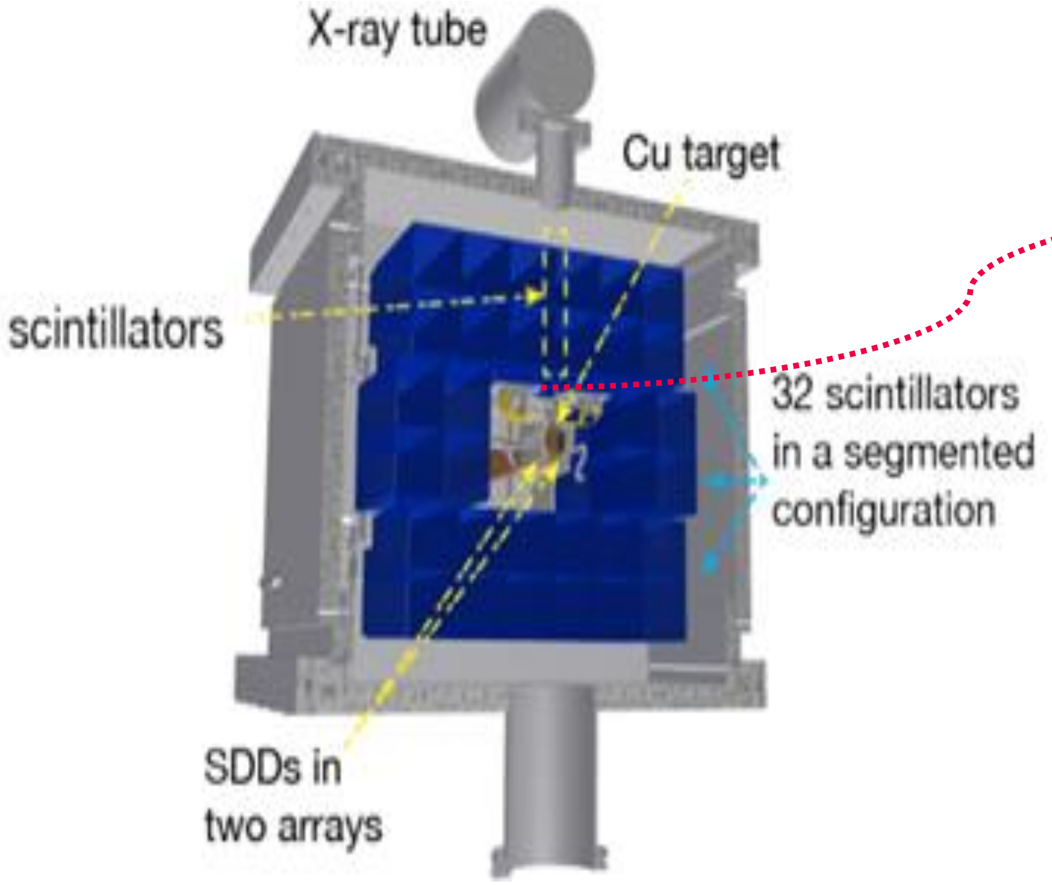
It takes into account: relativistic and radiative corrections, lamb-shift, Breit operator, ...



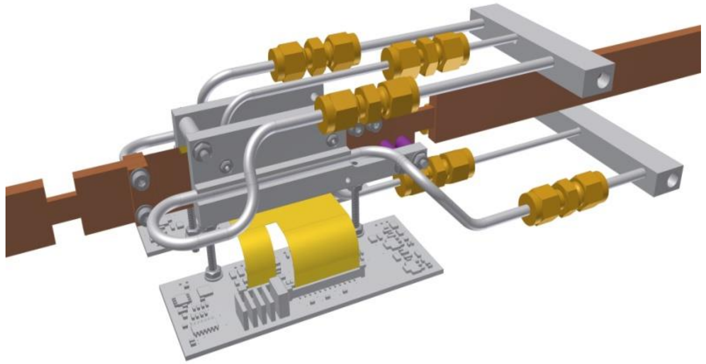
An e- in any level n>2 make a transition to level 2P.
The non-Paulian transition to level 1S produces the emission of a PEP violating X-ray.

2. The VIP2 experiment: purpose and apparatus.

Schematization of the VIP2 chamber



Target of VIP2

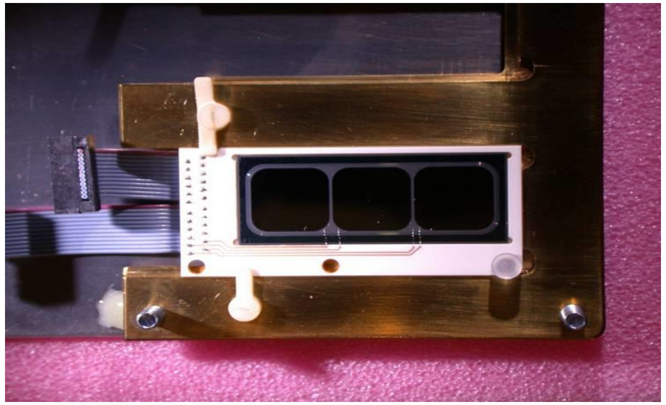


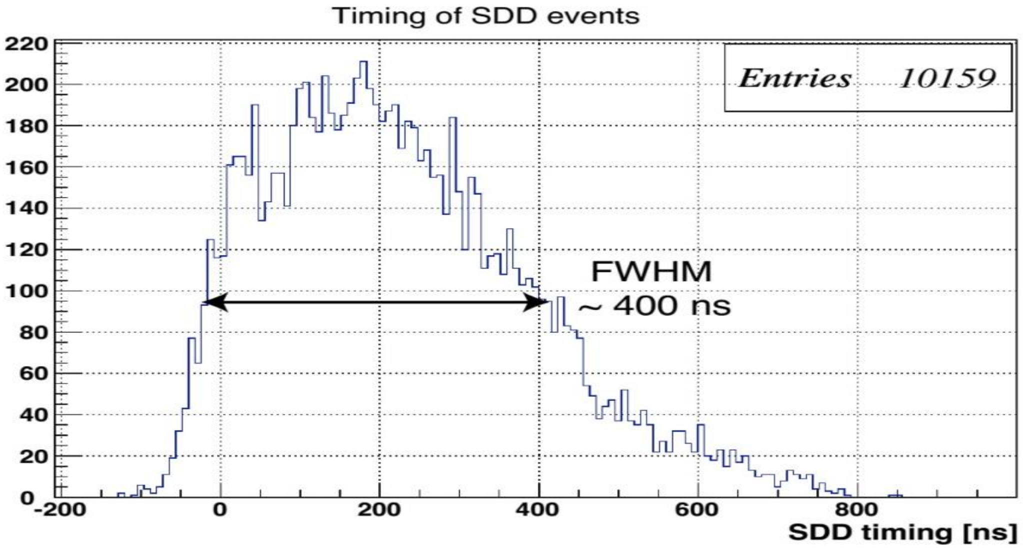
Characteristics of the target: the 2 strips (10 cm x 1 cm x 50 μm) are connected to an external generator by 2 thin copper bars. Due to the Joule effect, the current(100 A) heats the target to 20 ° C.
A water circuit cools the 2 copper strips so that the temperature of the detectors placed close to the target don`t increase by more than 2K.

2. The VIP2 experiment: Silicon Drift Detectors (SDDs)

In the apparatus the SDDs are organized in 2 chips containing 3 cells with 100 cm^2 of active area each. Those chips surround the target to optimize the coverage on a solid angle and are cooled to T≈ 100 K by liquid Argon to get a better performance in terms of energy resolution.

The energy resolution was tested with a Fe-55 source through a 25 μm thick Ti-plate. The lines of the K series of Mn and Ti are used to calibrate the spectrum and measure the energy resolution at 6 keV. This test resulted in a **resolution of about 150 eV at 6 KeV.**

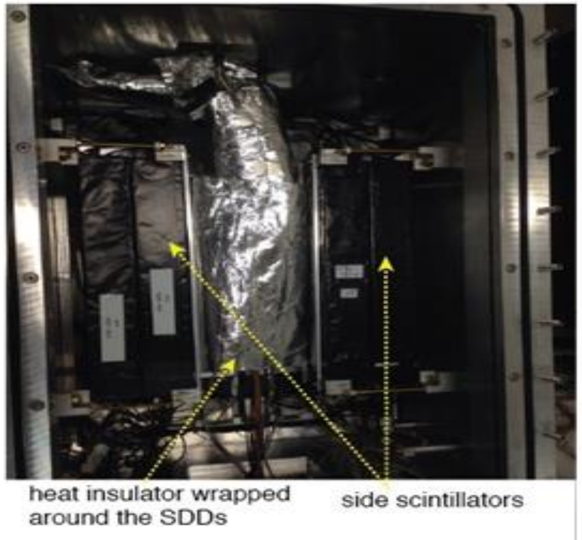




SDDs provide information on radiation energy and timing -> measurement performed with respect to the scintillator trigger: **400 ns (FWHM).**

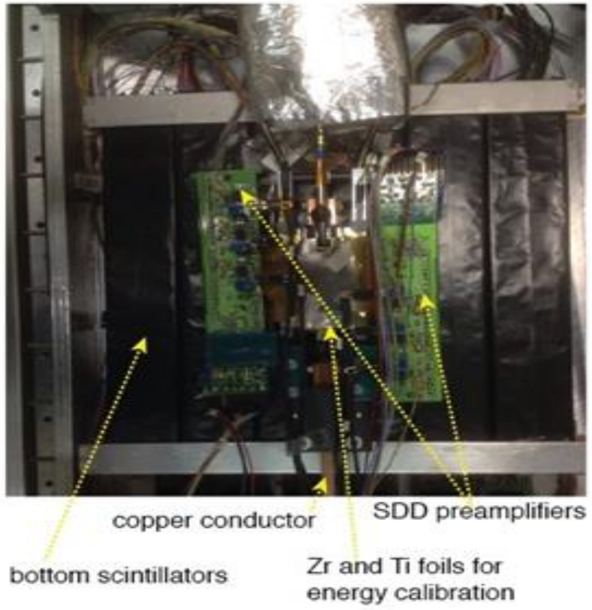
SUFFICIENT TEMPORAL RESOLUTION TO DISCRIMINATE THE BACKGOUND EVENTS

2. The VIP2 experiment: the VETO system



Used to select incident events with high energy RC unshielded from rock and environmental background.

Composed of 32 plastic scintillators measuring $40\,mm \times 32\,mm \times 250\,mm$ and covering a solid angle > 90% compared to the target.



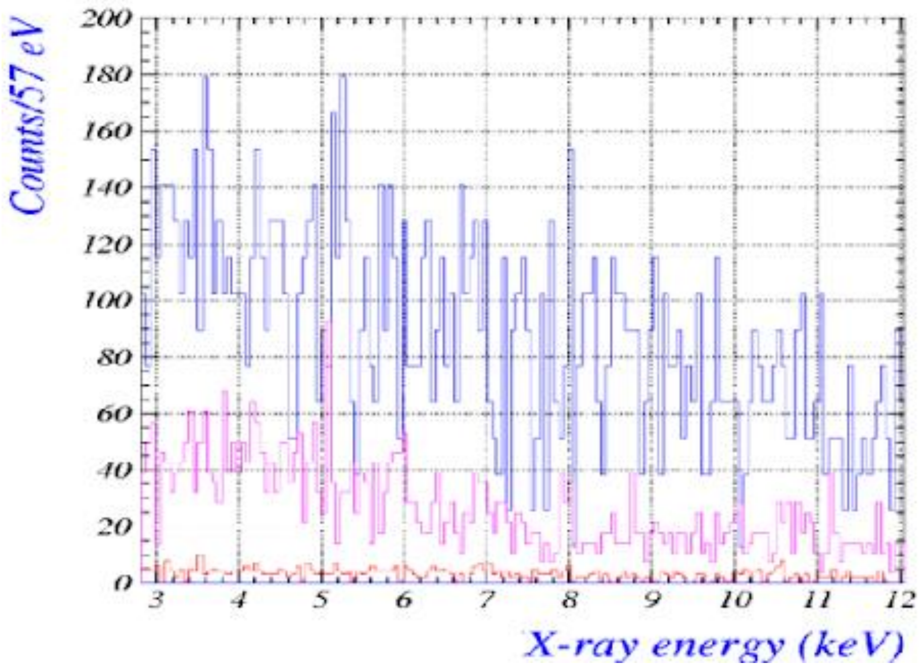
They are read by pairs of SiPM (with 3x3 cm^2 of active surface each) located at both ends.

THE ACTIVE SHIELD ALLOWS TO REDUCE THE BACKGROUND IN THE RANGE OF INTEREST FOR A VIOLATION X-RAY OF ABOUT 1 ORDER OF GRANDNESS

2. The VIP-2 experiment: location.

The experiment is taking place at National Laboratories of Gran Sasso (LNGS), an extremely low background environment inside the Gran Sasso mountain.

Graphic result of a test done with 2 CCD and normalized distribution



— LNF no sh.
— LNF with sh.
— LNGS with sh.

The background is reducted by a factor ≈ 20

2. The VIP-2 experiment: Improvements and goal

Improvements made compared to VIP:

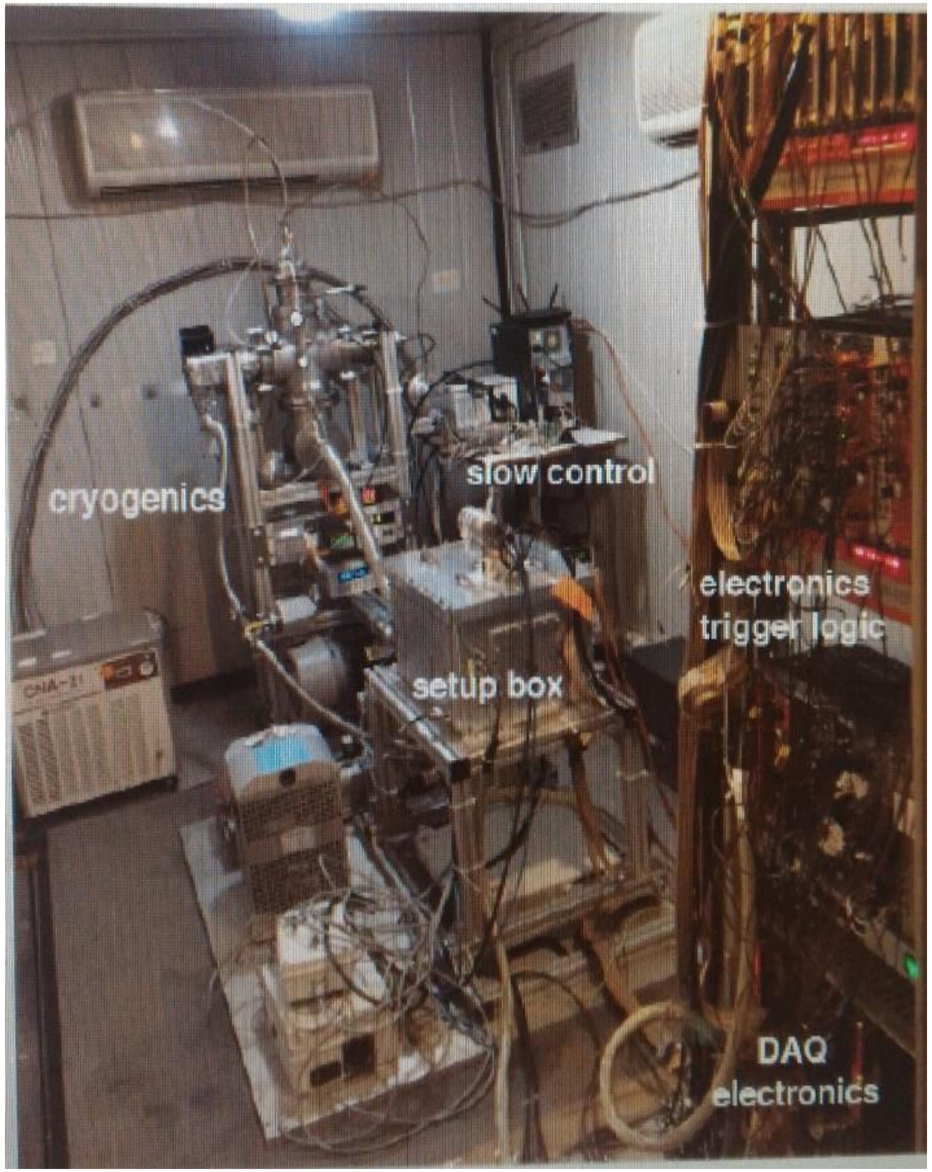
- More compact system → improves acceptance
- New target: 2 strip 10 cm x 1 cm x 50 μm
- Different cooling system for target (water)
- Current flowing into the target $\geqslant$ 100 A
- Nitrogen flushing to reduce radon in barrack
- New detectors SDD with better resolution, cooled with liquid Argon (~100 K).
- Veto system with plastic scintillators read by SiPM (Silicon Photomultiplier)
- Expected data acquisition 3-4 years.

Changes in VIP2	value VIP2 (VIP)	expected gain
acceptance	12 % (~ 1 %)	12
increase current	100 A (40 A)	> 2
reduced length	3 cm (8.8 cm)	1/3
total linear factor		8
energy resolution	170 eV (320 eV) @ 8 keV	4
reduced active area	6 cm ^{2} (114 cm ^{2})	20
better shielding and veto		5-10
higher SDD efficiency		1/2
background reduction		200 - 400
overall improvement		> 120

FUTURE GOAL

$$\boxed{\frac{\beta^2}{2} < 4.7 \times 10^{-29} \rightarrow 10^{-31}}$$

2. The VIP-2 experiment: photos of the apparatus



cryogenics to liquify
Ar for SDD cooling

helium compressor

vacuum chamber
with detectors inside

trigger logic

VME modules
for DAQ

3. The preliminary **upper LIMIT for the PEP violation** in copper got with data acquired until July 2017

Subtracting the spectra:

$$\boxed{\Delta N_x = 97 \pm 91}$$

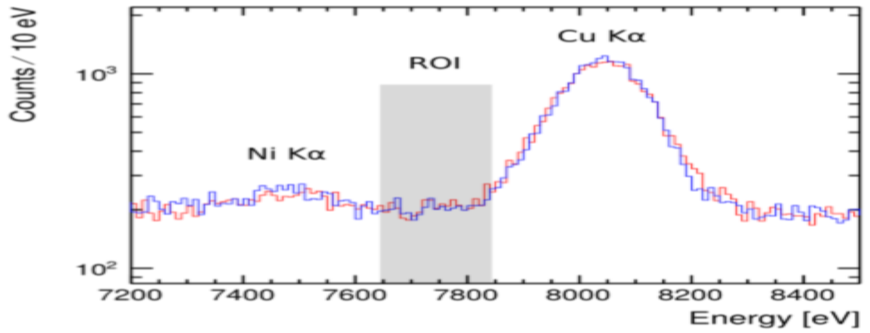
Normalized to 82 days

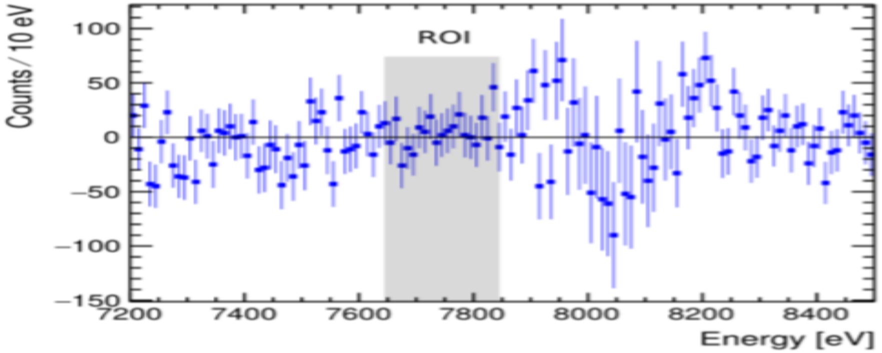
$$\Delta N_x \geq \frac{\beta^2}{2} N_{new} \frac{1}{10} N_{scatt} \times Eff_{Det} \rightarrow \boxed{\frac{\beta^2}{2} \leq 1.87 \times 10^{-29}}$$

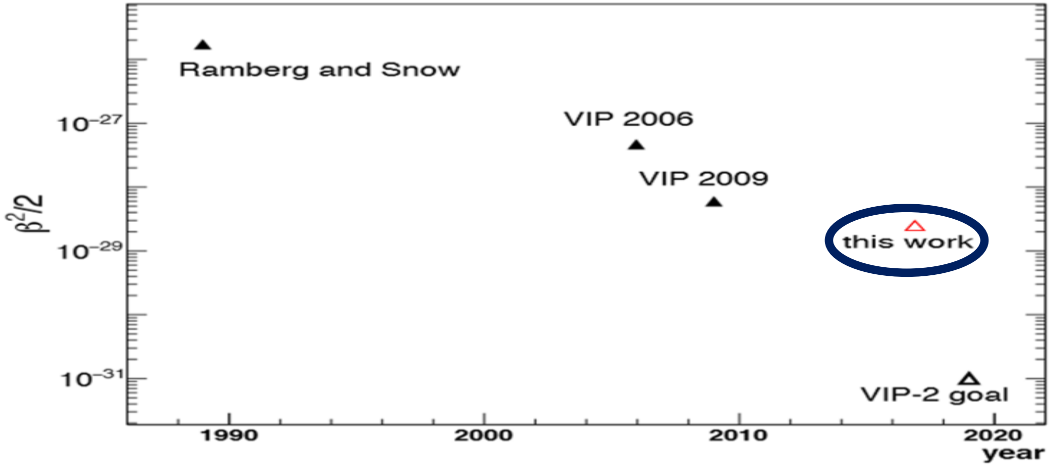
Confidence Level: 99.73%

P. Andreas et al., «Test of the Pauli Exclusion Principle for Electrons in the Gran Sasso Underground Laboratory», PHD Thesis, 2019.

We note how with VIP2 we have managed, in the space of about 82 days of data collection, to determine a value of the upper limit of the PEP violation slightly better than that obtained by VIP in about three years of measurement.







4. New significant improvements of the VIP-2 apparatus performed during 2018

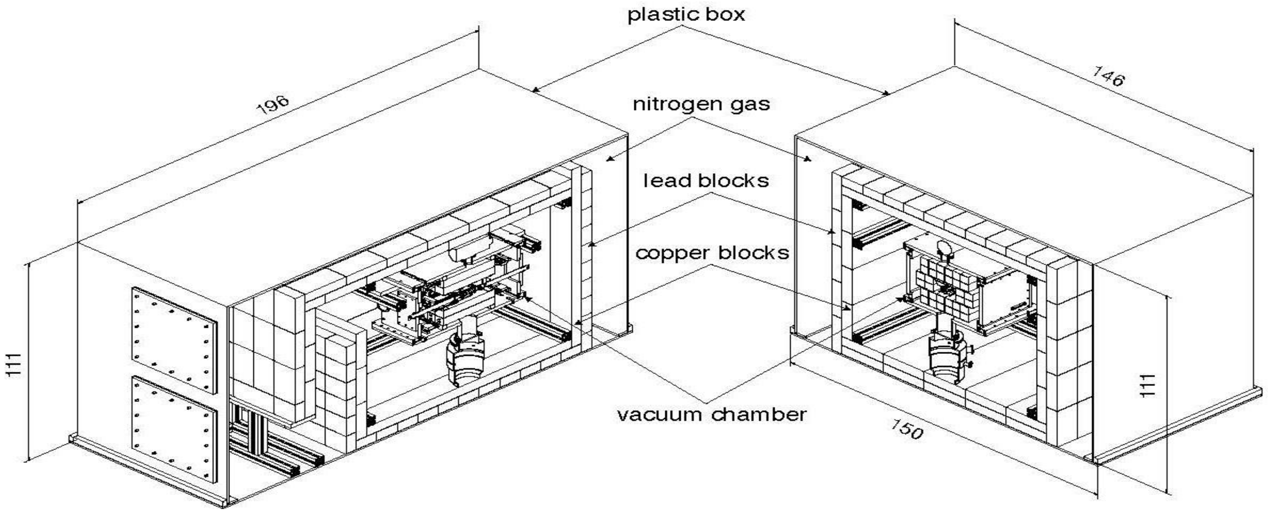
A further upgrade of the VIP-2 setup was performed in April 2018:

- the SDDs arrays were replaced with two arrays 2×8 for a total of 32 SDDs

  $Eff_{det} = 1.82\% \rightarrow 4\%$

- new thinner $(25\ \mu m)$ copper targets were realized, in order to reduce the X-rays absorption inside the target.

In April 2019 the final configuration of the VIP-2 experimental apparatus was completed with the passive shielding, made of two layers of lead and copper blocks.



The passive shield will kill most of the background due to environmental gamma radiation.

FIGURE: *Perspective views of the VIP-2 apparatus with passive shielding, with the dimensions in cm. Nitrogen gas with a slight over pressure with respect to the external air will be circulated inside a plastic box in order to reduce the radon contamination.*

4. A NEW preliminary upper LIMIT for the PEP violation probability of electrons in copper calculated in the new present configuration of the apparatus

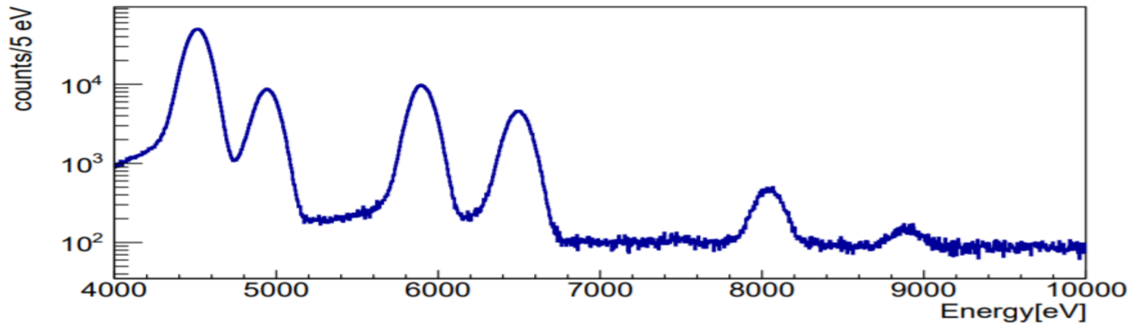
A preliminary result has been calculated using 39 days of data acquired during 2018 in the new present configuration of the apparatus, before to complete the passive shielding.

$$\boxed{\Delta N_x = 93 \pm 90}$$

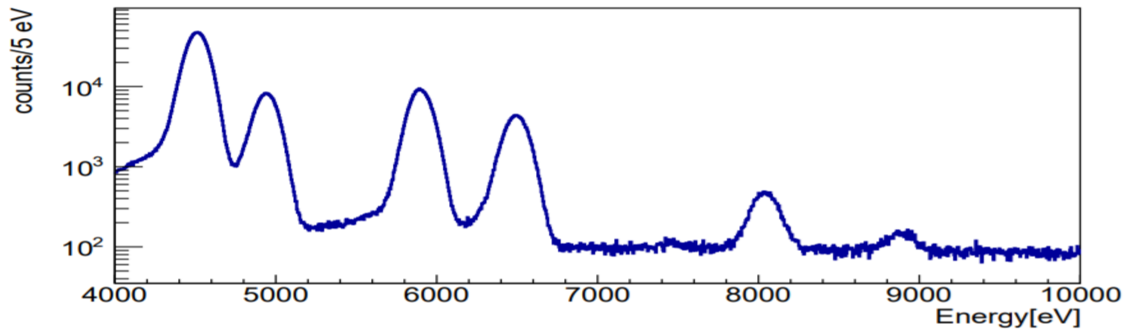
$$\boxed{\frac{\beta^2}{2} \leq 1.6 \times 10^{-29}}$$

Confidence Level: 99.73%

The upgrades done for the new configuration of the apparatus improved the result got in the space of about 82 days of data collection with the previous setup in about half of data taking time.



Energy calibrated spectra with current circulating on target (100 A)



Energy background calibrated spectra with current off normalized to 39 days

5. The «Ramberg & Snow» model

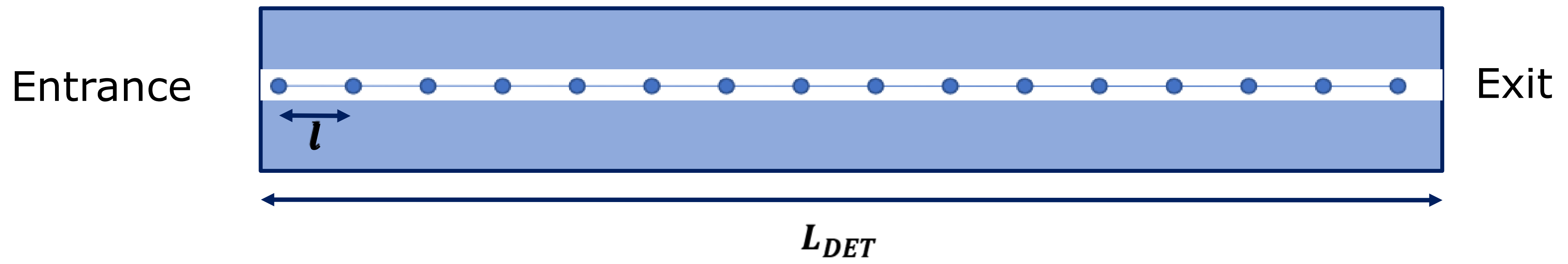
In the experiment VIP the number of scatterings for the single electron was calculated as:

$$\frac{L_{DET}}{l}$$

L_{DET} → Linear length of the target

l → Average free electron path

In VIP2 the target length is 10 cm (≈7.5 cm actually crossed by current) and the free electron average path in copper is 40 nm. The number of scatterings of the single electron for RS is $\sim\mathbf{2\times10^6}$



5. The «Random Walk» model

The drift velocity of the electron in the copper is:

$$v_d = \frac{I}{newz} \sim 5\ mm/s$$

n is the density of electrons for each m^3, *e* is the elementary charge, w and z are the width and thickness of the target

The mean time of crossing the target for the single electron is **Δt=16 seconds**.

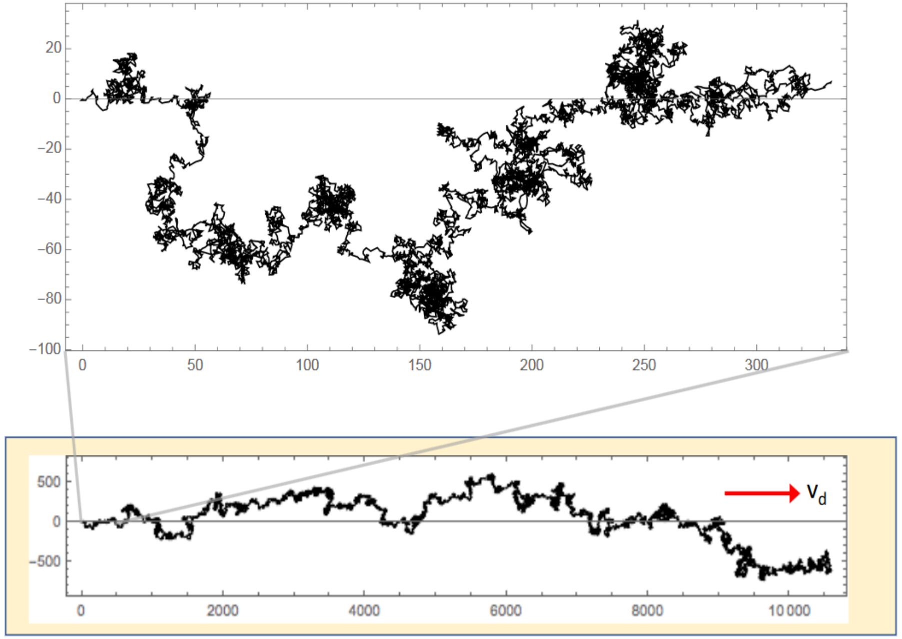
Average time between two collisions is: $\tau = 2,5 \times 10^{-14} s$

The number of scatterings of the single electron can be calculated as:

$$\frac{\Delta t}{\tau} = 6,4 \times 10^{14}\ scatterings \gg 2 \times 10^{6}$$

Following the «Random walk» model the upper limit set by VIP-2 could be brought to a value of:

$$\frac{\beta^2}{2} \leq \sim 10^{-40}$$



E.Milotti et al., «On the importance of Electron Diffusion in a Bulk-Matter Test of the Pauli Exclusion Principle», Entropy, 2018.

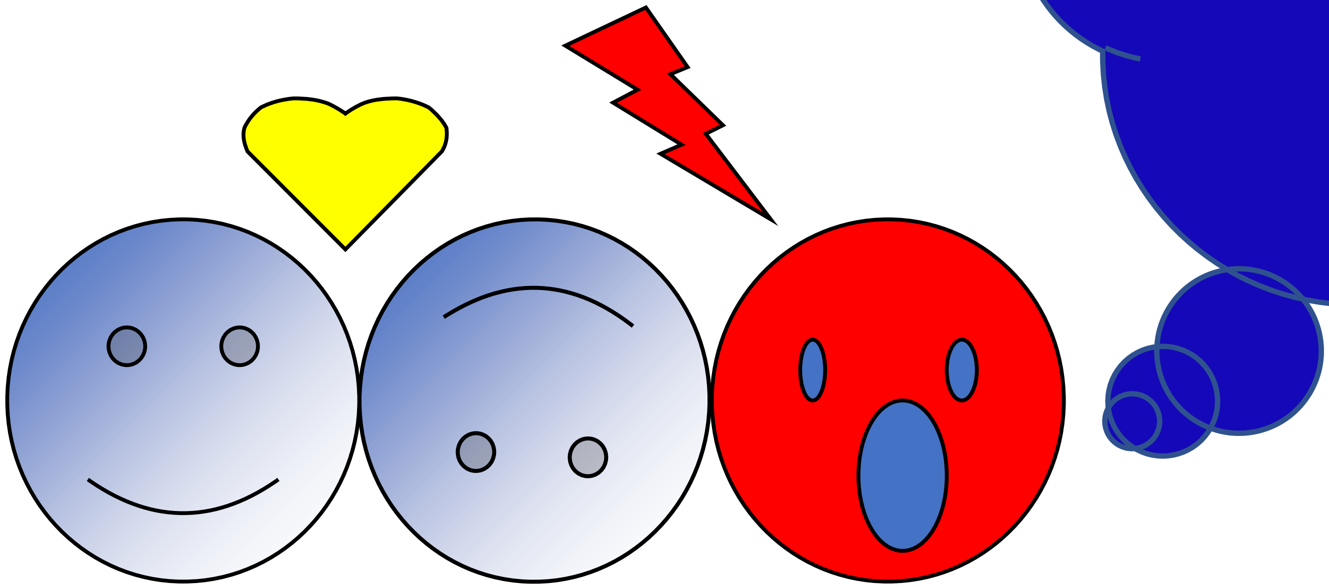
A particular recognition goes to ….

FQXi
FOUNDATIONAL QUESTIONS INSTITUTE

The support from the Foundational Question Institute (FQXi) in the framework of the project: ***"Events' as we see them: experimental test of the collapse models as a solution of the measurement-problem." (FQXi Grant number: FQXi-RFP-1505)***

John Templeton Foundation

The support from the John Templeton Foundation in the framework of the project: ***58158: Hunt for the "impossible atoms": the quest for a tiny violation of the Pauli Exclusion Principle, Implications for physics, cosmology and philosophy.***



THANK YOU ALL FOR YOUR ATTENTION !!!

Ignatiev & Kuzmin Model

I & K built the simplest algebra of creation and destruction operators which incorporates in the parameter β the small violations of the Pauli exclusion principle.

Creation and destruction operators connect 3 states :

- $|0\rangle$ empty
- $|1\rangle$ single occupation state
- $|2\rangle$ no-standard state of double occupation (two fermions in the same state)

These are the operation which connect all the three states:

$$\boxed{\begin{array}{ll} a^{+}|0\rangle = |1\rangle & a|0\rangle = 0 \\ a^{+}|1\rangle = \beta|2\rangle & a|1\rangle = |0\rangle \\ a^{+}|2\rangle = 0 & a|2\rangle = \beta|1\rangle \end{array}}$$

The parameter β express the violation degree of the transition

$|1\rangle \rightarrow |2\rangle$

Two fermions are in the same state ->
Forbidden by the Pauli exclusion principle

Note that for $\beta \rightarrow 0$ we find the Fermi-Dirac statistic and the Pauli exclusion principle is absolutely valid.

Ignatiev-Kuzmin model

(A. Yu. Ignatiev and V. A. Kuzmin, Yad. Fiz. 46 (1987) 786, and ICTP preprint IC/87/13 (1987))

Three basic states: $|0\rangle, |1\rangle, |2\rangle$

The actions of creation and destruction operators:

$$a^+|0\rangle = |1\rangle \qquad a|0\rangle = 0$$
$$a^+|1\rangle = \beta|2\rangle \qquad a|1\rangle = |0\rangle$$
$$a^+|2\rangle = 0 \qquad a|2\rangle = \beta|1\rangle$$

$$a^+ = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & \beta & 0 \end{pmatrix} \qquad a = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & \beta \\ 0 & 0 & 0 \end{pmatrix} \longrightarrow N = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{pmatrix}$$

With $[N, a^+] = a^+$, $[N, a] = -a$

The following relation is obtained: $N = \dfrac{1}{1-\beta^2+\beta^4}\left[\left(2-\beta^2\right)I + \left(-1+2\beta^2\right)a^+a + \left(-2+\beta^2\right)aa^+\right]$

By applying the perturbation theory to the Hamiltonian:

$$H = H_0 + H_{\mathrm{int}} = EN + \varepsilon V$$

$$V = a^2 a^+ + a^+ a^2 + a a^+ a + h.c.$$

with $E = \sum_n E_n$ and $V = \sum_{i<j} V_{ij}$

$$\varepsilon = E$$

It's possible to determine the transition probabilities:

$$W_{01} = 2\frac{\varepsilon^2}{E^2}(1 - \cos Et)$$

$$W_{02} = 0$$

$$W_{12} = 2\beta^2 \frac{\varepsilon^2}{E^2}(1 - \cos Et)$$

Pauli violating transition rate proportional to β^2

Historical quotations

- in the words of W. Pauli

PEP lacks a clear, intuitive explanation

... 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 assumptions.

I HAD ALWAYS THE FEELING AND I STILL HAVE IT TODAY, THAT THIS IS A DEFICIENCY.

... The impression that the shadow of some incompleteness [falls] here on the bright light of success of the new quantum mechanics seems to me unavoidable.

W. Pauli, Nobel lecture 1945

Calculation of limit

$$\boxed{\Delta N_x \geq \frac{\beta^2}{2} N_{new} \frac{1}{10} N_{scatt} \times Eff_{riv}}$$

The factor of detection efficiency has been calculated using a simulation in GEANT4 and it is about 4%

$$\Delta N_x = 41 \pm 66$$

$$N_{new} = \left(\frac{1}{e}\right) \Sigma I \Delta t$$

$$\frac{D}{\mu}$$

The lenght of the electronic path in copper is ≈7.5 cm

Mean free path = $\mu = 3.9 \cdot 10^{-8} m$

The capture probability of the electron by a copper atom is more than 1/10 respect to the scattering probability.

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

Confidence level (3σ) 99.7%

Copper Transition Table

Transition	Pauli Obeyning Transition	Pauli violating transition	Energy Difference
	Standard transition Energy [eV]	Energy [eV]	$E_{standard} - E_{VIP}$ $[eV]$
$2p_{1/2} ==\gg 1s_{1/2}$ $(K_{\alpha 2})$	8,047.78	7,728.92	318,86
$2p_{3/2} ==\gg 1s_{1/2}$ $(K_{\alpha 1})$	8,027.83	7,746.73	279.84
$3p_{1/2} ==\gg 1s_{1/2}$ $(K_{\beta 2})$	8,905.41	8,529.54	375.87
$3p_{3/2} ==\gg 1s_{1/2}$ $(K_{\beta 1})$	8,905.41	8,531.69	373.72
$3d_{3/2} ==\gg 2p_{3/2}$ $(L_{\alpha 2})$	929.70	822.84	106.86
$3d_{5/2} ==\gg 2p_{3/2}$ $(L_{\alpha 1})$	929.70	822.83	106.87
$3d_{3/2} ==\gg 2p_{1/2}$ $(L_{\beta 1})$	949.84	841.91	107.93
$3s_{1/2} ==\gg 2p_{1/2}$	832.10	762.04	70.06
$3s_{1/2} ==\gg 2p_{3/2}$	811.70	742.97	68.73
$3d_{5/2} ==\gg 1s$ Direct Radiative Recombination	8,977.14	8,570.82	406.32

"Evaluation of the anomalous X-ray energy in VIP experiment", 2013, INFN-13-19/LNF
"Evaluation of the anomalous X-ray energy in VIP experiment, some values from Dirac-Fock method", 2013, INFN-13-20/LNF
"Evaluation of the X-ray transition energies for the pauli-principle-violating atomic transitions in several elements by using Dirac-Fock method", 2013, INFN-13-21