ÖAW AUSTRIAN ACADEMY OF SCIENCES

VIP2: Searches for tiny violations of spin statistics in an underground laboratory

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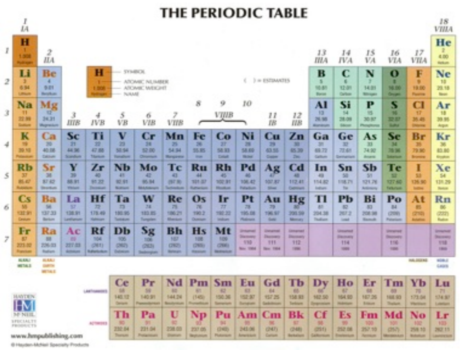
https://www.lngs.infn.it/en/pagine/vip-eng

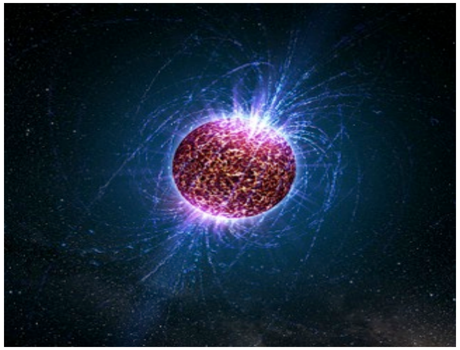
FWF
Project P25529-N20
Project P30635-N36

John Templeton Foundation

Outline

- PEP - a solid rule of nature (i.e. pillar of QM)
- Motivation for experimental testing PEP
- Experimental methods for testing
- Results obtained with different experiments
- Present status and next steps
- Summary and outlook





VIP-2 Collaboration

ITALY
INFN laboratori Nazionali di Frascati: C. Curceanu, S. Bartalucci, A. Clozza, L. de Paolis, A. d'Uffizi, C. Guaraldo, M. Iliescu, K. Piscicchia(*), E. Sbardella, A. Scordo, H. Shi, D. Sirghi, F. Sirghi, L.Sperandio (*) and Museo torico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Roma
INFN Laboratori Nazionali del Gran Sasso: M. Laubenstein
Università and INFN Trieste: E. Milotti

AUSTRIA
SMI-Vienna: C. Berucci, M. Cargnelli, J. Marton, A. Pichler, E. Widmann, J. Zmeskal

FRANCE
Univ. Rennes: S. di Matteo

GERMANY
TUM-Muenchen: O. Vazquez Doce

ROMANIA
IFIN-HH, Bucharest: M. Bragadireanu, D. Pietreanu, T. Ponta

SWITZERLAND
CERN: S. Bertolucci Now: Univ. Bologna
Univ. Neuchatel: J.-P. Egger

Putting the Pauli exclusion principle on trial

The exclusion principle is part of the bedrock of physics, but that hasn't stopped experimentalists from devising cunning ways to test it.

If we tightly grasp a stone in our hands, we neither expect it to vanish nor leak through our flesh and bones. Our experience is that stone and, more generally, solid matter is stable and impenetrable. Last year marked the 50th anniversary of the demonstration by Freeman Dyson and Andrew Lenard that the stability of matter derives from the Pauli exclusion principle. This principle, for which Wolfgang Pauli received the 1945 Nobel Prize in Physics, is based on ideas so prevalent in fundamental physics that their underpinnings are rarely questioned. Here, we celebrate and reflect on the Pauli principle, and survey the latest experimental efforts to test it.

The exclusion principle (EP), which states that no two fermions can occupy the same quantum state, has been with us for almost a century. In his Nobel lecture, Pauli provided a deep and broad-ranging account of its discovery and its connections to unsolved problems of the newly born quantum theory. In the early 1920s, before Schrödinger's equation and Heisenberg's matrix algebra had come along, a young Pauli performed an extraordinary feat when he postulated both the EP and what he called "classically non-describable two-valuedness" – an early hint of the existence of electron spin – to explain the structure of atomic spectra.

At that time the EP met with some resistance and Pauli himself was dubious about the concepts that he had somewhat recklessly introduced. The situation changed significantly after the introduction in 1925 of the electron-spin concept and its identification with Pauli's two-valuedness, which derived from the empirical ideas of Landé, an initial suggestion by Kronig, and an independent paper by Goudsmit and Uhlenbeck. By introducing the picture of the electron as a small classical sphere with a spin that could point in just two directions, both Kronig and Goudsmit and Uhlenbeck, were able to compute the fine-structure splitting of atomic hydrogen, although they still missed a critical factor of two. These first steps were followed by the relativistic calculations of Thomas, by the spin calculus of Pauli, and finally, in 1928, by the elegant wave equation of Dirac, which put an end to all resistance against the concept of spin.

Pauli himself was puzzled by the principle.

Portrait of a young Pauli at Svein Rosseland's institute in Oslo in the early 1920s, when he was thinking deeply on the applications of quantum mechanics to atomic physics.

However, a ... time. Just bef... made signific... lication in 19... between spin... a relativistica... determines th... or anticommu... EP for spin-½... connection, a... based on their...

Catalina Curceanu, LNF-INFN, **Dmitry Budker**, Helmholtz Institute, JGU Mainz and UC Berkeley, **Edward J Hall**, Harvard University, **Johann Marton**, Stefan Meyer Institute, Vienna, and **Edoardo Milotti**, University of Trieste and INFN–Sezione di Trieste.

Beguilingly simple

The EP is beguilingly simple to state, and many physicists have tried to skip relativity and find direct proofs that use ordinary quantum mechanics alone – albeit assuming spin, which is a genuinely relativistic concept. Pauli himself was puzzled by the principle, and in his Nobel lecture he noted: "Already in my original paper I stressed the circumstance that I was unable to give a logical rea-

CERN Courier
March 2018

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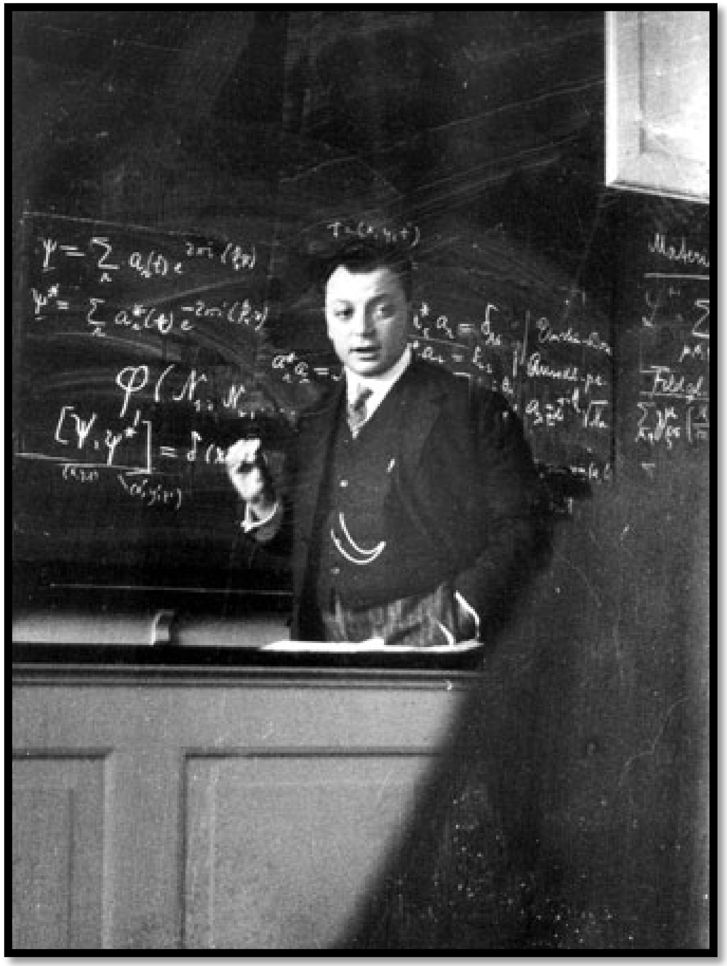
W. Pauli 1925

"In an atom there cannot be two or more equivalent electrons for which the values of all four quantum numbers coincide. If an electron exists in an atom for which all of these numbers have definite values, then the state is occupied."

W.Pauli, Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren, Zeitschrift für Physik 31 (1925) 765.



Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren.

Von **W. Pauli** jr. in Hamburg.

(Eingegangen am 16. Januar 1925.)

Zeitschrift für Physik 1925

Es kann niemals zwei oder mehrere äquivalente Elektronen im Atom geben, für welche in starken Feldern die Werte aller Quantenzahlen n, k_1, k_2, m_1 (oder, was dasselbe ist, n, k_1, m_1, m_2) übereinstimmen. Ist ein Elektron im Atom vorhanden, für das diese Quantenzahlen (im äußeren Felde) bestimmte Werte haben, so ist dieser Zustand „besetzt".

punkte vorhanden zu sein. Das Problem der näheren Begründung der hier zugrunde gelegten allgemeinen Regel über das Vorkommen von äquivalenten Elektronen im Atom dürfte wohl erst nach einer weiteren Vertiefung der Grundprinzipien der Quantentheorie erfolgreich angreifbar sein.

Hamburg, Institut für theoretische Physik.

„Klassisch nicht beschreibbare Zweideutigkeit des Elektron" → 4. Quantenzahl

Several proofs exist in the context of QFT which differ in clarity and in their quality of physical insight.

Lüders and Zumino lay out a very clean set of assumptions in their 1958 proof:

I. The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)
II. Two operators of the same field at points separated by a spacelike interval either commute or anticommute (Locality)
III. The vacuum is the state of lowest energy
IV. The metric of the Hilbert space is positive definite
V. The vacuum is not identically annihilated by a field

(G. Lüders and B. Zumino, Phys. Rev. **110** (1958) 1450)

PEP Tests - atomic transitions

From S.R. Elliott et al., Found. Phys. 42 (2012) 1015

Process	Type	Experimental limit	$\frac{1}{2}\beta^2$ limit
Atomic transitions			
$\beta^- + \mathrm{Pb} \to \check{\mathrm{Pb}}$	Ia		3×10^{-2}
$e^-_{pp} + \mathrm{Ge} \to \check{\mathrm{Ge}}$	Ia		1.4×10^{-3}
$e^-_I + \mathrm{Cu} \to \check{\mathrm{Cu}}$	II		1.7×10^{-26}
$e^-_I + \mathrm{Cu} \to \check{\mathrm{Cu}}$	II		4.5×10^{-28}
$e^-_I + \mathrm{Cu} \to \check{\mathrm{Cu}}$	II		6.0×10^{-29}
$e^-_I + \mathrm{Pb} \to \check{\mathrm{Pb}}$	II		1.5×10^{-27}
$e^-_f + \mathrm{Pb} \to \check{\mathrm{Pb}}$	IIa		2.6×10^{-39}
$\mathrm{I} \to \check{\mathrm{I}} + \text{X-ray}$	III	$\tau > 2 \times 10^{27}$ sec	3×10^{-44}
$\mathrm{I} \to \check{\mathrm{I}} + \text{X-ray}$	III	$\tau > 4.7 \times 10^{30}$ sec	6.5×10^{-46}

Recently created fermions interacting with system

Distant fermions interacting with system

Stable system transition

Experimental tests

- Atomic transitions
- Nuclear transitions
- Nuclear reactions
- PEP-forbidden nuclear structures
- PEP forbidden atomic structures
- Neutrino statistics
- Astrophysics and cosmology

Requirements

Due to the anticipated very small PEP violation effects (if any) strong requirements for experiments are obvious:

- Large number of fermions probing the PEP
- Characteristic signal (i.e. unique indicator)
- High efficient detection
- Low background

Experiment of Goldhaber & Scharff-Goldhaber

(identification of beta-rays with atomic electrons; 1948)

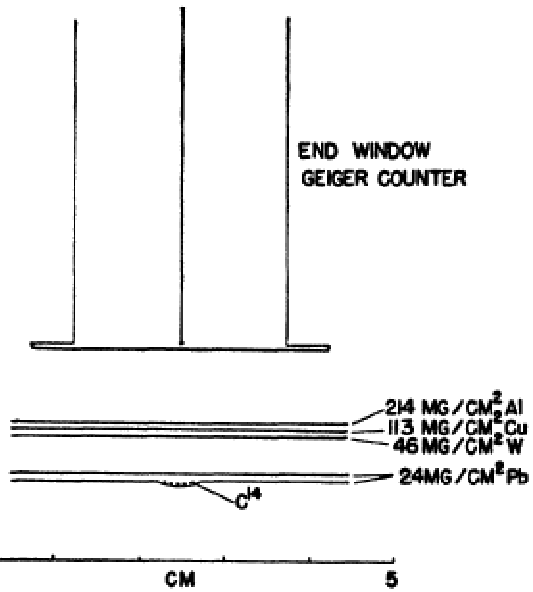
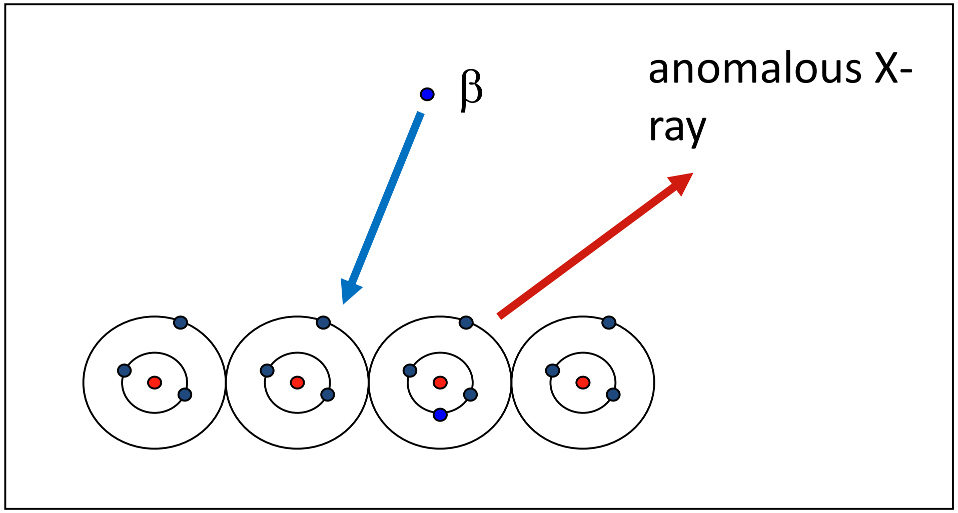


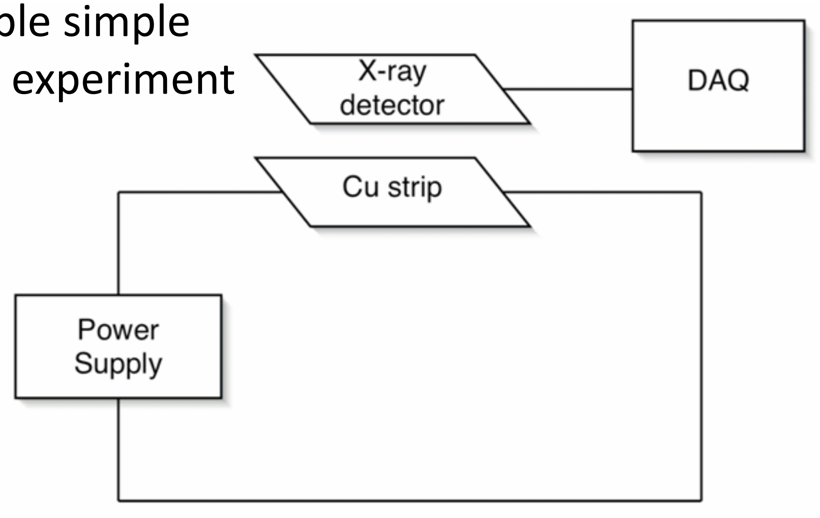
FIG. 1. Arrangement used in search for photons from beta-rays stopped in lead.

The data of Goldhaber and Scharff-Goldhaber were reinterpreted by Reines and Sobel to obtain a limit on the validity of Pauli Exclusion Principle in 1974



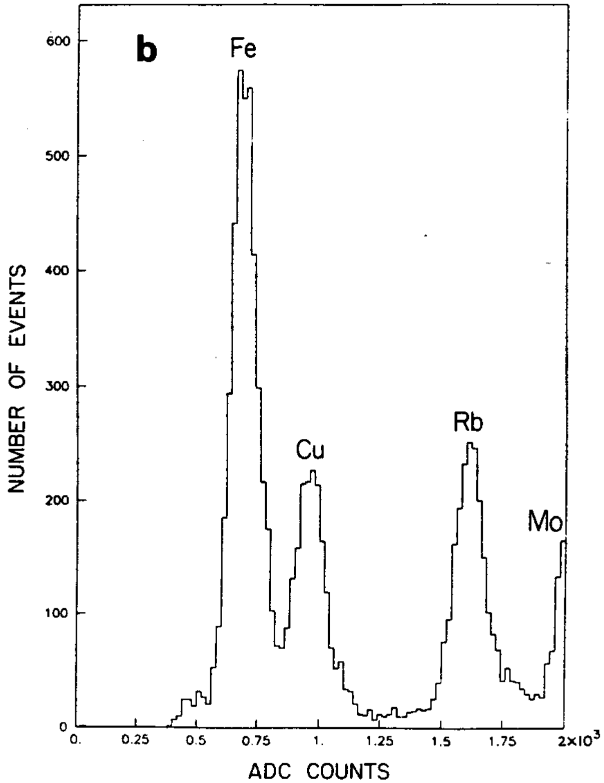
Ramberg & Snow experiment

Instead of a radioactive source a power supply delivers *fresh=„new“* electrons to test PEP.
Remarkable simple table-top experiment



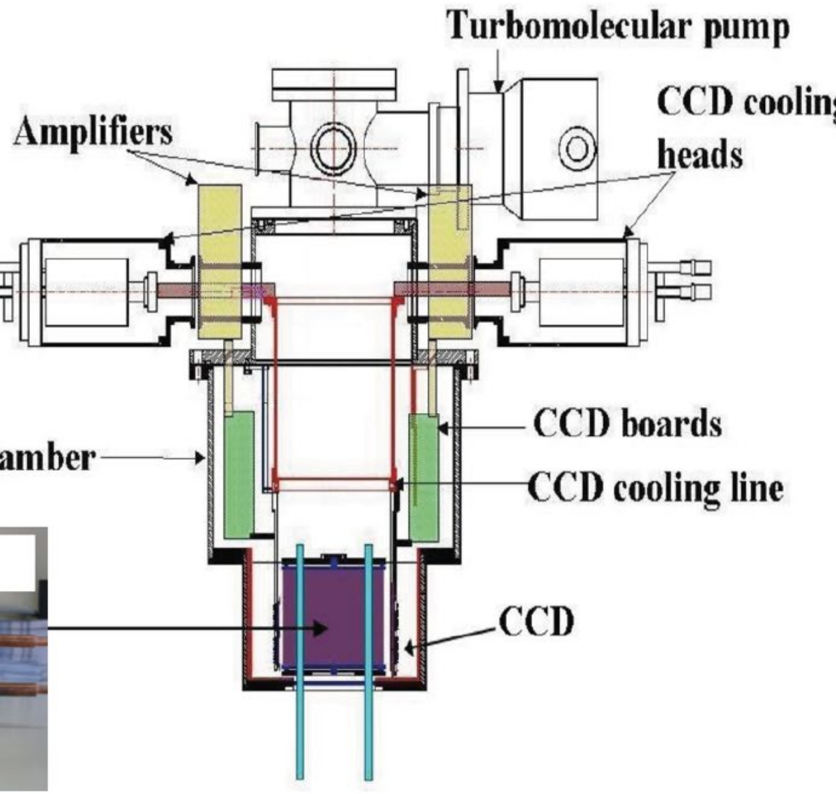
E. Ramberg and G. A. Snow, Phys. Lett. **B238** (1990) 438

X-ray detector:
Closed proportional tube
Detector calibration
ΔE ~ 1200 eV @ 8keV

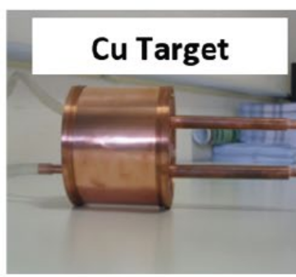


- **The X-rays detector: proportional tube counter situated above a thin strip of cooper which is connected to a controlled 50A power supply;**
- **Energy resolution of about 1200eV of FWHM at 7keV;**
- **The measurements lasted 2 months; data with and without current were taken, in basement of the Muon building at Fermilab;**
- **Two background runs: one with a piece of cooper that never had current running through it and another where no cooper is present .**

VIP Apparatus



High purity Cu (99.997%)
R= 45 mm
H=88 mm
D=50 μm



X-ray spectra with the VIP final setup at LNF

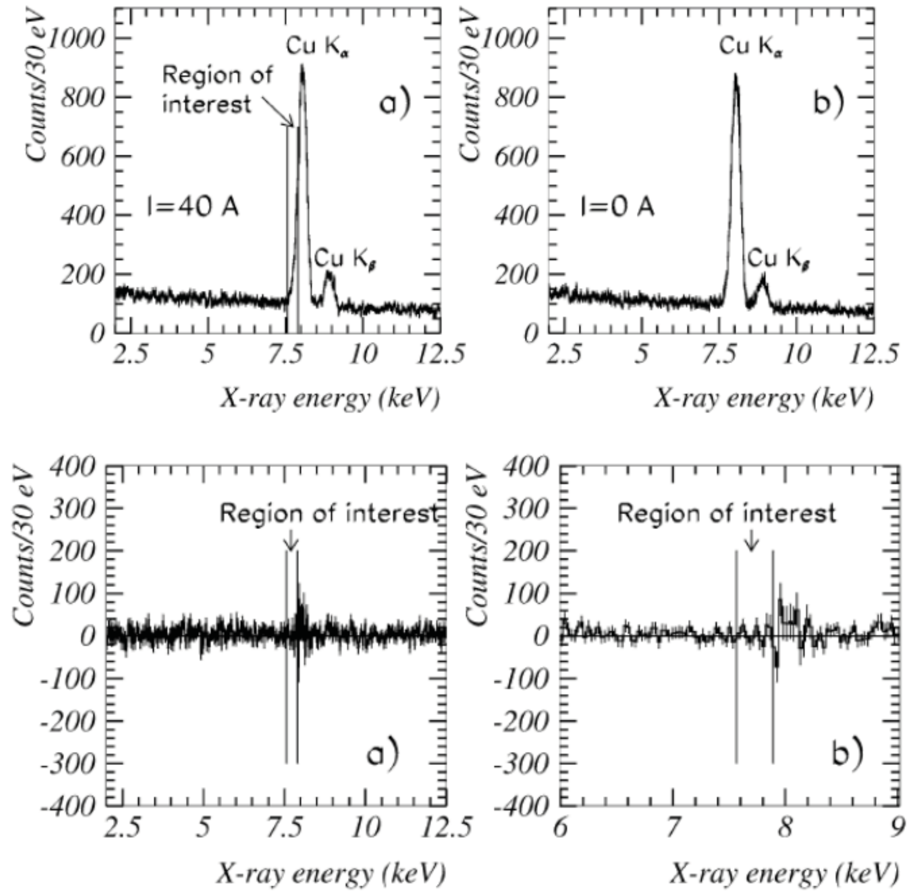
2 types of measurements:

14510 min with I=40A
14510 min with I=0A

Subtraction gives:

$$\Delta N_X = -21 \pm 73$$

$$\frac{\beta^2}{2} \leqslant \frac{3 \times 73}{4.9 \times 10^{29}} = 4.5 \times 10^{-28}$$

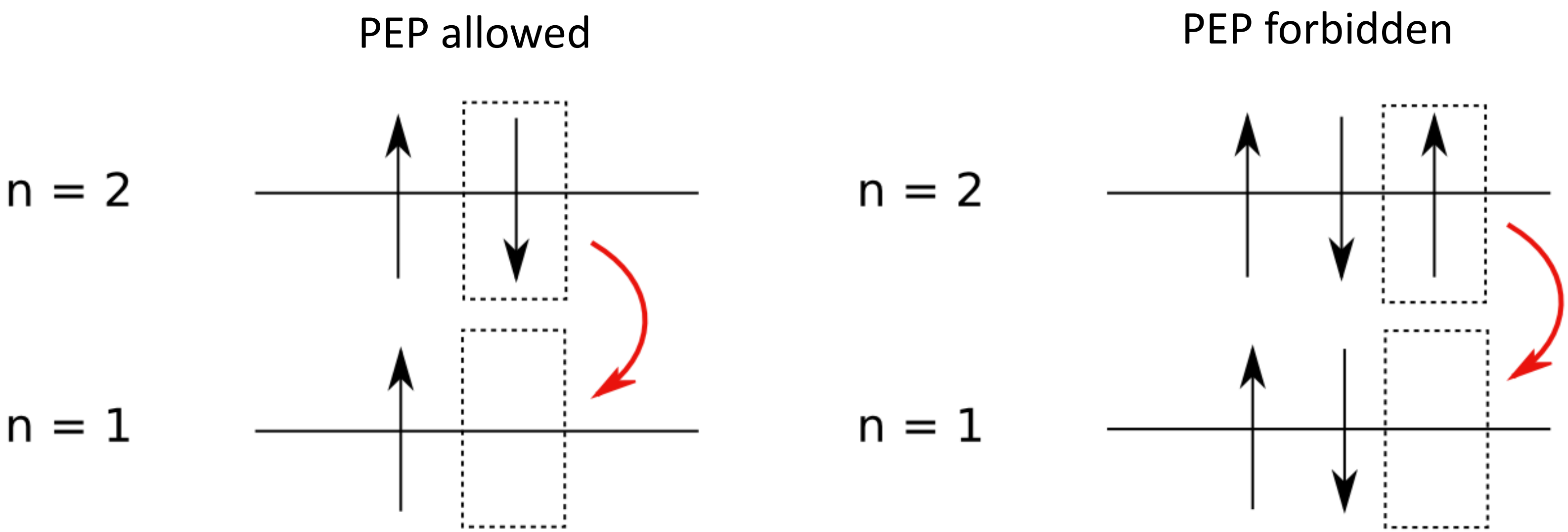


VIP Collaboration / Physics Letters B 641 (2006) 18–22

The proof of PEP in theory is not simple ... already pointed out by Pauli himself

Experimental tests of the validity limits of PEP are complicated and based on different assumptions for specific systems

Principle of VIP2



normal	PEP-forbidden
8048 eV	7747 eV

Cu $K\alpha_1$ transition energies.

ΔE ≈ 300 eV resolvable by X-ray spectroscopy

Calculated transition energies in Cu

Table 2. Energy shift and transition probability of vPp-atomic transitions for copper.

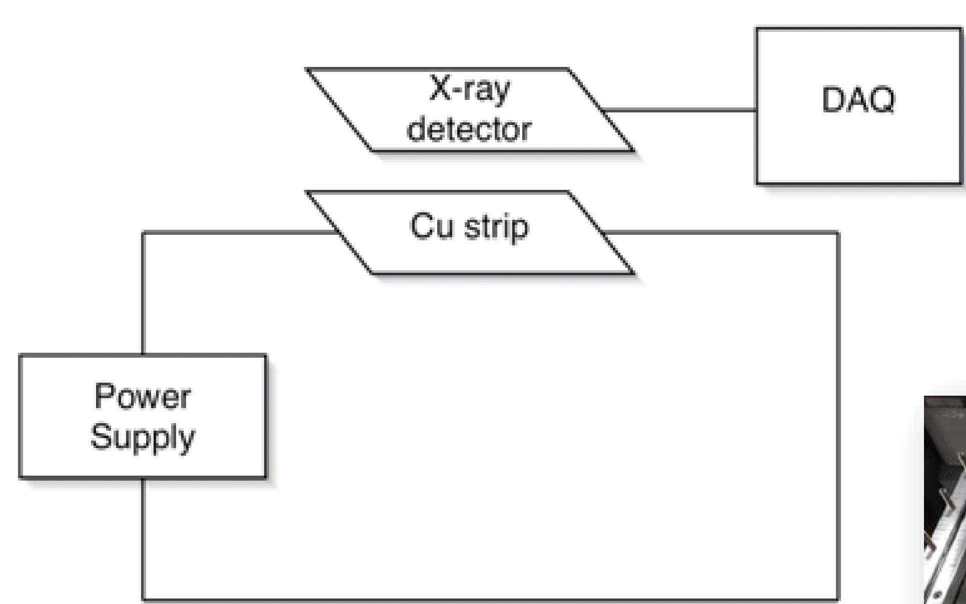
Transition	Experimental energy (eV)	Calculated non-vPp (eV)	Calculated vPp: Energy (eV) and Transition probability (s^{-1})		Calc. energy diff. non-vPp - vPp (eV)
$2p_{1/2} \rightarrow 1s_{1/2}$ ($K_{\alpha 2}$)	8027.83	8027.85	7728.92	2.5690970E+14	298.93
$2p_{3/2} \rightarrow 1s_{1/2}$ ($K_{\alpha 1}$)	8047.78	8047.79	7746.73	2.6372675E+14	301.06
$3p_{3/2} \rightarrow 1s_{1/2}$ ($K_{\beta 1}$)	8905.29	8905.41	8531.69	2.6737747E+13	373.72
$3d_{5/2} \rightarrow 2p_{3/2}$ ($L_{\alpha 1}$)	929.70	929.72	822.83	3.4922759E+08	106.89
$3d_{1/2} \rightarrow 2p_{1/2}$ ($L_{\beta 1}$)	949.80	949.84	841.91	3.0154308E+08	107.93
$3d \rightarrow 1s$ (DRR)	8979.00	8977.14	8570.82	1.2125697E+06	406.32

H. Shi, E. Milotti, J. Marton, A. Pichler, et al.
Experimental search for the violation of Pauli Exclusion Principle.
European Physics Journal C, 78(4):319, 2018

The pre-VIP experiment limit

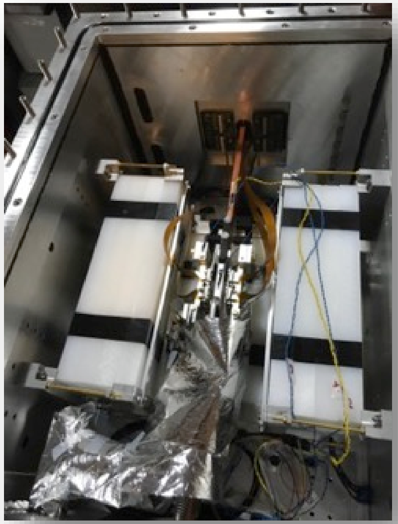
Ramberg and Snow (RS)

Phys. Lett. ***B238*** *(1990) 438*

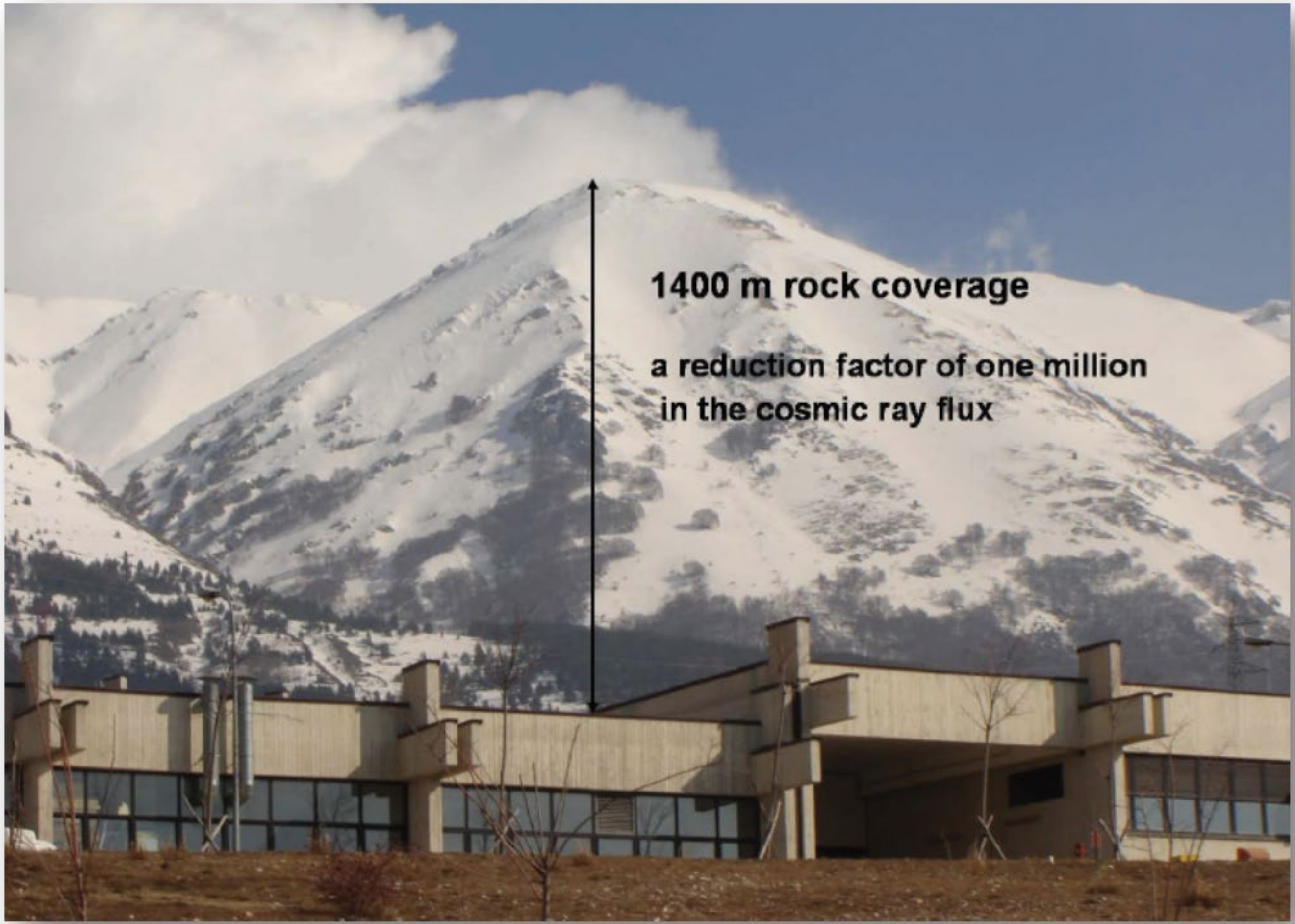


X-ray detecto (RS experiment)r:
Closed proportional tube
Detector calibration
$\Delta E \sim 1200$ eV @ 8keV

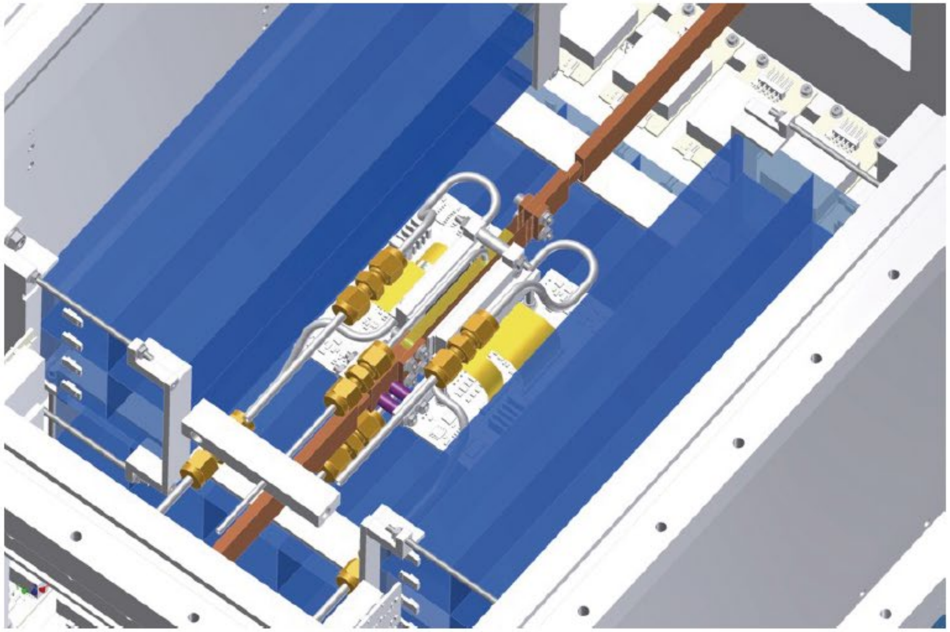
$$N_X \geq \beta^2 \left(0.90 \cdot 10^{28}\right)$$
$$\beta^2 / 2 \leq 1.7 \cdot 10^{-26} (> 95\% C.L.)$$

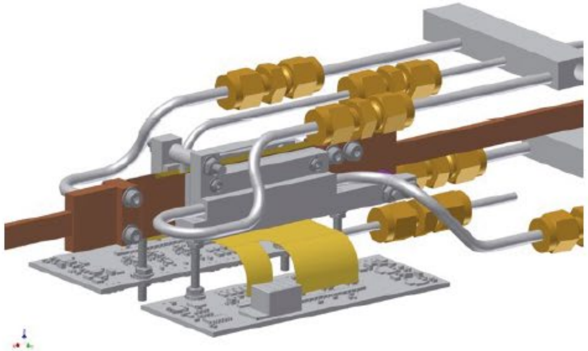


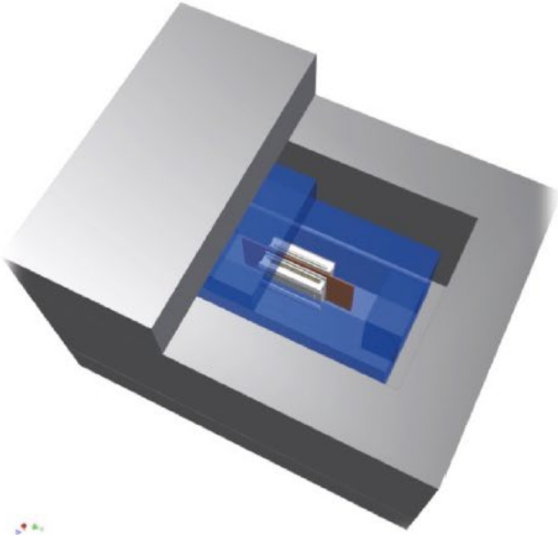
VIP2: Target and SDDs
Improvement in energy resolution factor 10

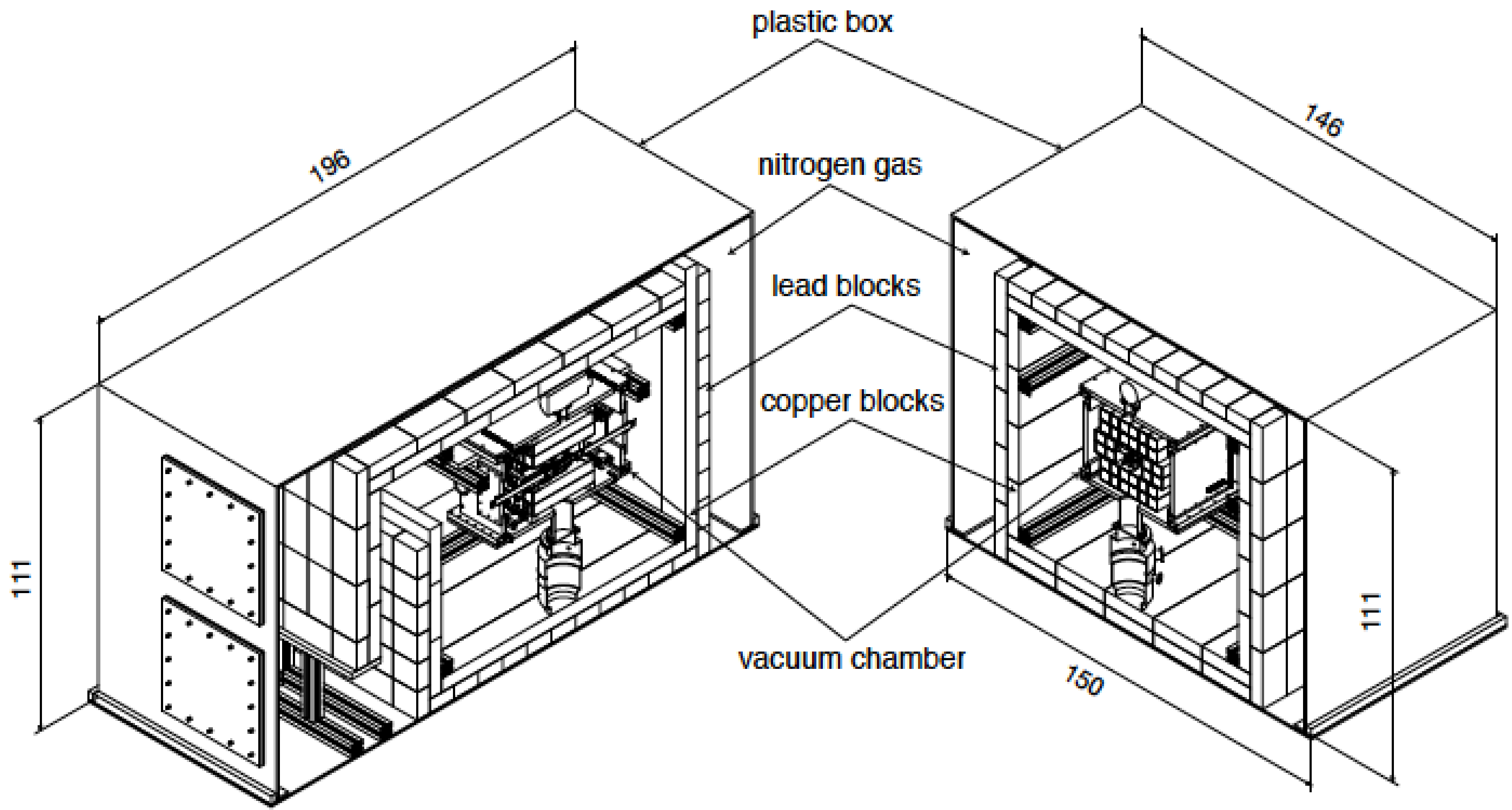

1400 m rock coverage
a reduction factor of one million
in the cosmic ray flux

Sketch of the VIP2 Setup:
Cu foil, 2x3 SDD x-ray detectors



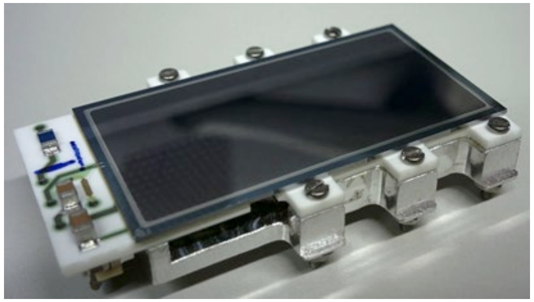




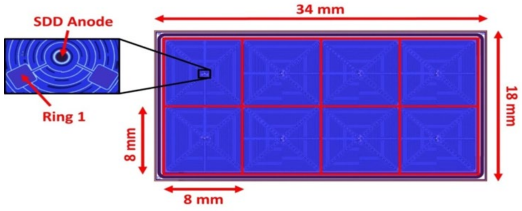

plastic box
nitrogen gas
lead blocks
copper blocks
vacuum chamber
196
111
146
111
150

VIP-2 Features

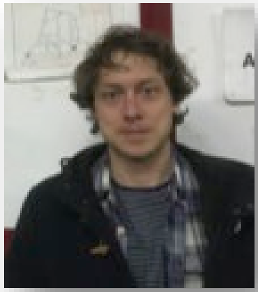
- Largely improved test of PEP in the lepton sector (electrons) – „atom stability test“, „spin statistics test“



- Use of detectors developed for spectroscopy of hadronic (kaonic) atoms
- Shielding by rock coverage → LNGS



- Background reduction in underground experiments – important for all high sensitivity underground experiments

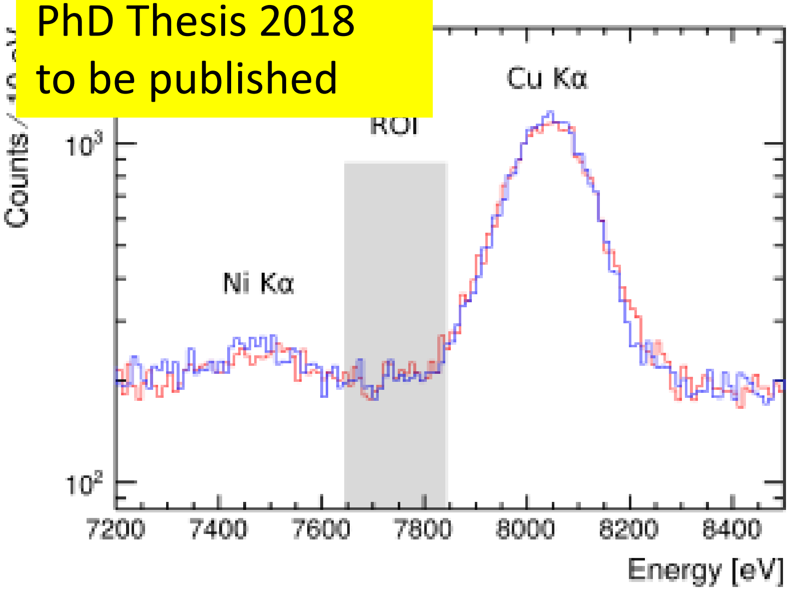


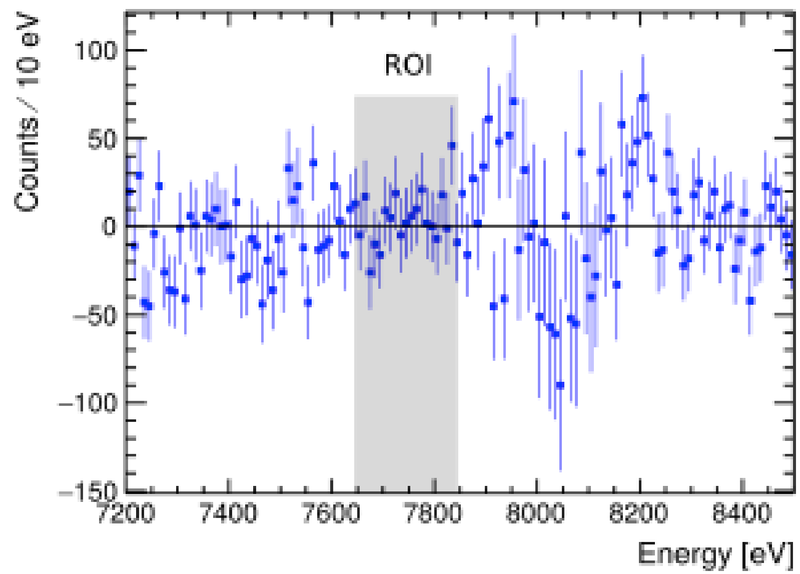
Spectrum subtraction in the ROI yields a new upper limit on the probability for a violation of the PEP of:

$$1.87 \times 10^{-29}$$

Improvement compared to the VIP experiment by factor 2.5

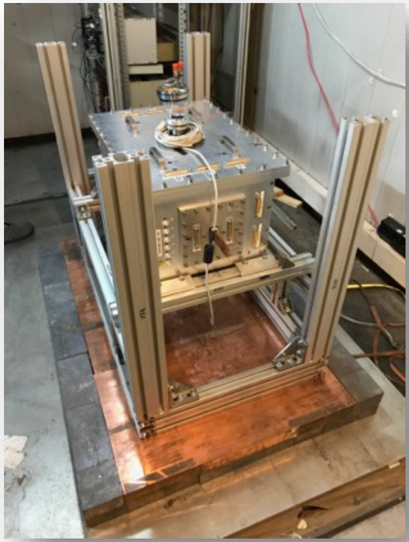
Dr. Andreas Pichler
PhD Thesis 2018
to be published

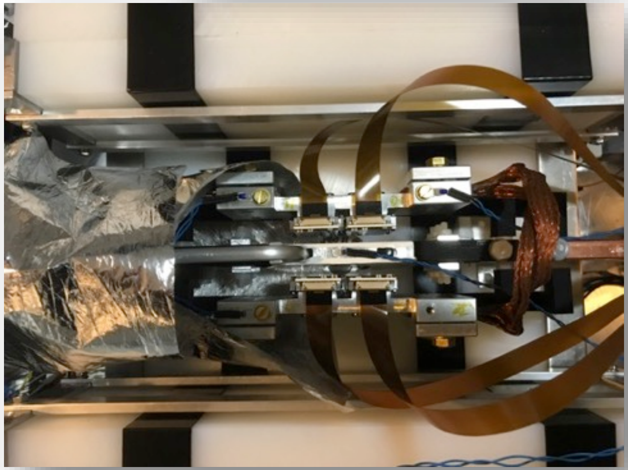




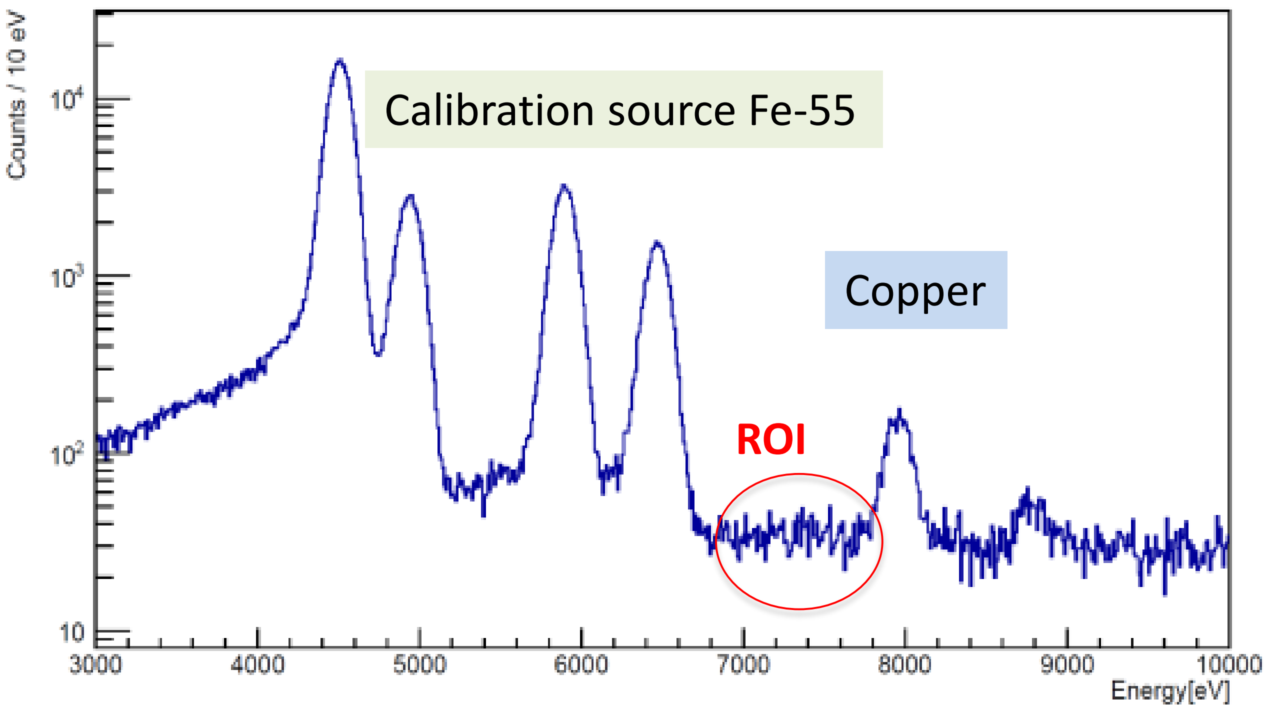
Recent activities 2018

- VIP2 vacuum system improvement and new SDDs (4x2 type)
- Test of the apparatus at SMI in Vienna
- Transport and Installation of VIP2, installation on platform
- After tests - ready for passive shielding benefit factor about 100



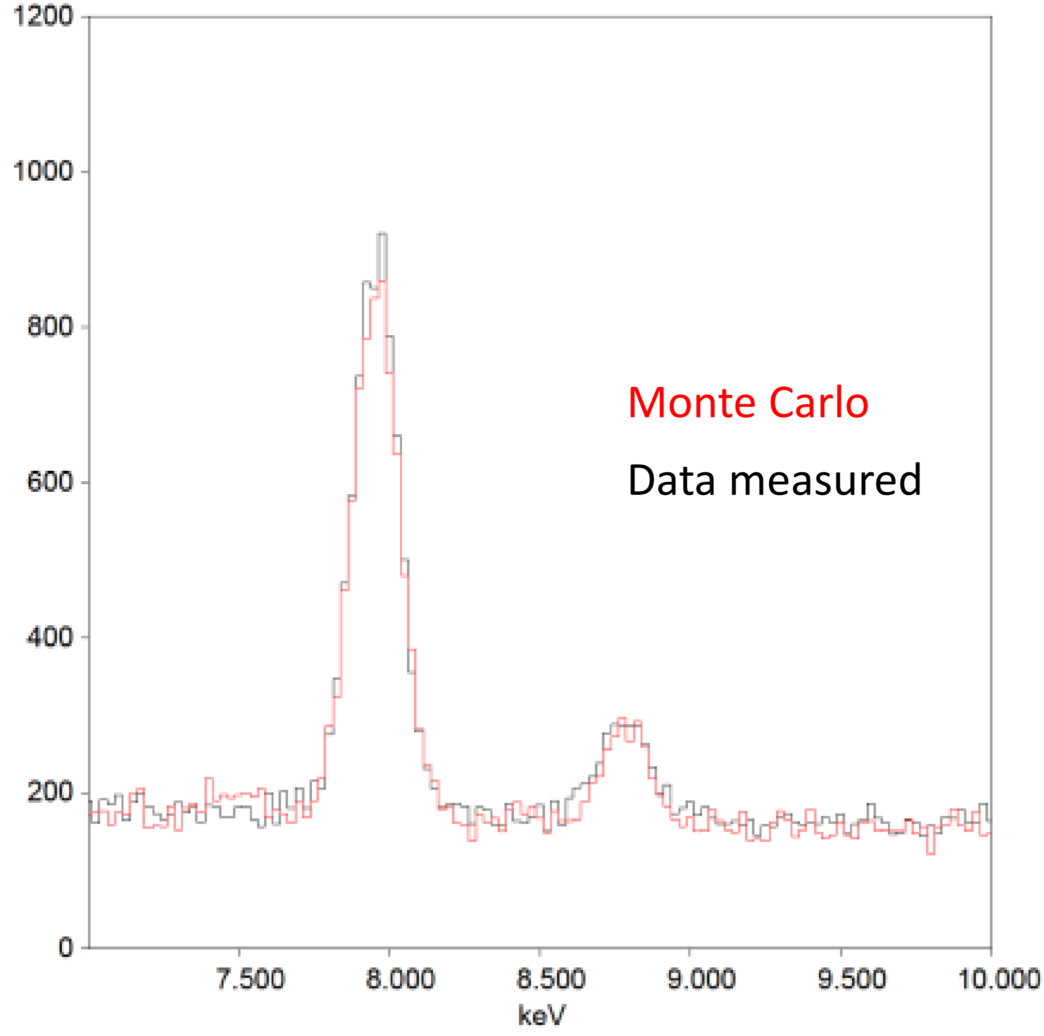


Energy-calibrated X-ray spectrum
with VIP2 set-up (6 days) in Gran Sasso

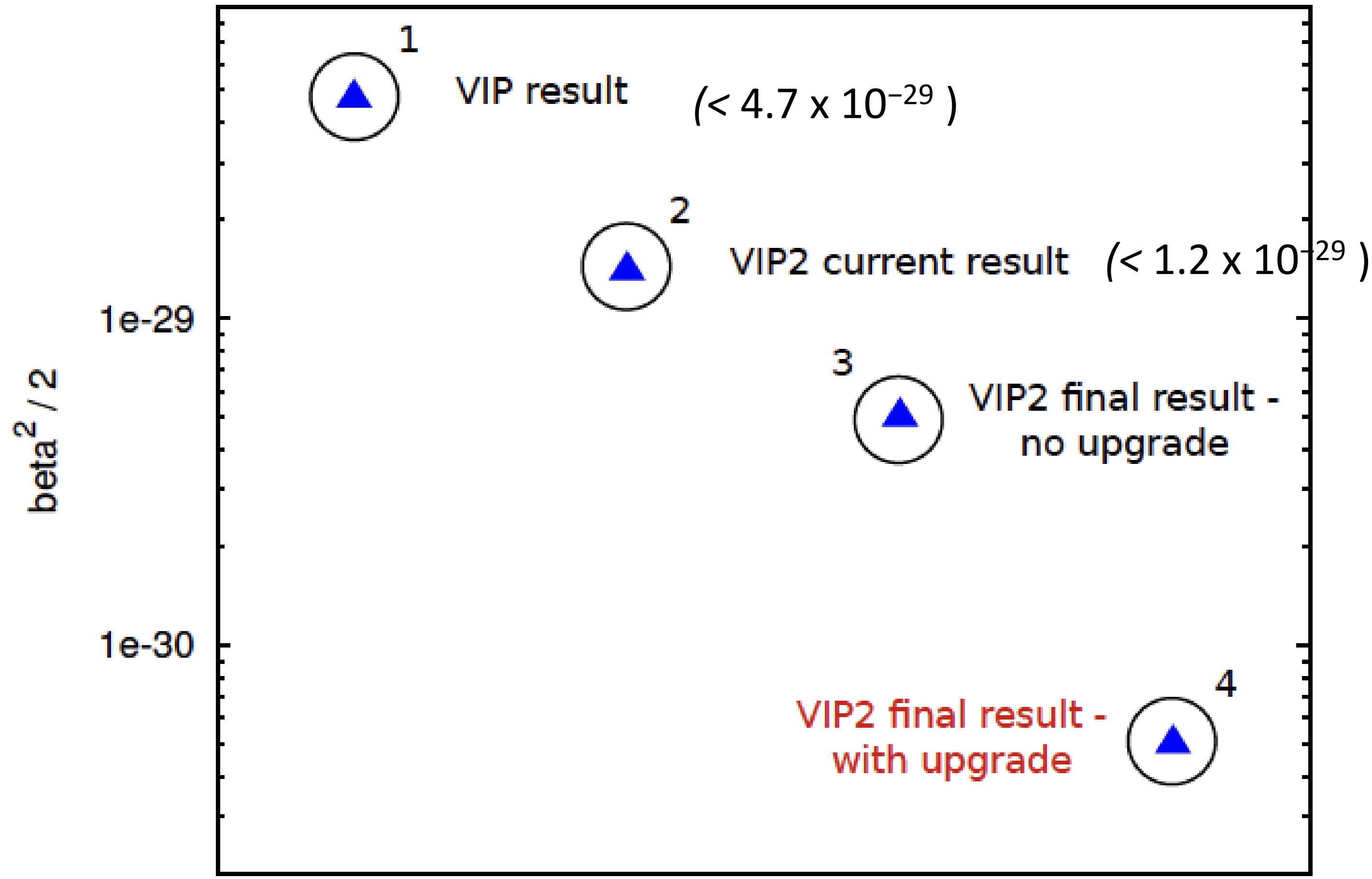


Energy Resolution ≈ 150 eV (FWHM) at 6 keV

LNGS Background studies with Monte-Carlo



Toward the final result



New Studie of the VIP(2) Method

On the Importance of Electron Diffusion in a Bulk-Matter Test of the Pauli Exclusion Principle, Entropy 2018, 20(7), 515; https://doi.org/10.3390/e20070515:

entropy

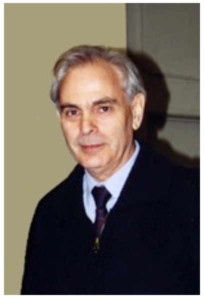
MDPI

Article

On the Importance of Electron Diffusion in a Bulk-Matter Test of the Pauli Exclusion Principle

Edoardo Milotti [1,*], Sergio Bartalucci [2], Sergio Bertolucci [3], Massimiliano Bazzi [2], Mario Bragadireanu [2,4], Michael Cargnelli [2,5], Alberto Clozza [2], Catalina Curceanu [2,4,6], Luca De Paolis [2], Jean-Pierre Egger [7], Carlo Guaraldo [2], Mihail Iliescu [2], Matthias Laubenstein [8], Johann Marton [2,5], Marco Miliucci [2], Andreas Pichler [2,5], Dorel Pietreanu [2,4], Kristian Piscicchia [2,6], Alessandro Scordo [2], Hexi Shi [9], Diana Laura Sirghi [2,4], Florin Sirghi [2,4], Laura Sperandio [2], Oton Vázquez Doce [2,10], Eberhard Widmann [5] and Johann Zmeskal [2,5]

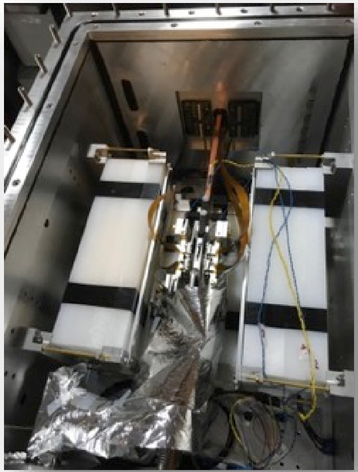
exposed in this paper is better than the bound found with the RS approach by a factor 5.2×10^{12}. In the case of VIP-2 ($\overline{I} = 100$ A) with a mean traversal time of about 10 s, there are on average at least 2.8×10^{17} close encounters instead of about 1.8×10^{6}, and the bound improves by a factor 1.6×10^{11}. If we take the more recent VIP-2 experiment [5], this translates into a bound on the violation parameter: $\beta^2/2 < 2.6 \times 10^{-40}$.



Lev Okun
1929-2015

"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."

Thank you



SPARE

Stability of matter (E. Lieb)

Reviews of Modern Physics, Vol. 48, No. 4, October 1976

"We take a piece of metal. Or a stone. When we think about it, we are astonished that this quantity of matter should occupy so large a volume. Admittedly, the molecules are packed tightly together, and likewise the atoms within each molecule. But why are the atoms themselves so big?... Answer: only the Pauli principle, 'No two electrons in the same state.' That is why atoms are so unnecessarily big, and why metal and stone are so bulky."

Dyson then goes on to say that without the Pauli principle

> "We show that not only individual atoms but matter in bulk would collapse into a condensed high-density phase. The assembly of any two macroscopic objects would release energy comparable to that of an atomic bomb."

VIP2 - Funding

- Till October 2017 FWF (final report submitted January 2018), new application for VIP2 to FWF, evaluation positive, funding approved

- Started March^{1st}, 2018 new FWF Project P30635-N36 (duration 3 yrs (2018-2021), about 250 kEUR)

Pauli exclusion principle test in an underground laboratory
Dipl.Ing. Dr. Johann MARTON
P 25529-N20

From the referee report

The VIP experiment is presently the state of the art for testing the Pauli Exclusion Principle. The project successfully improved the previous version, as planned, and the new results are a substantial improvement. It was certainly a scientific success.

signature supervisor

DISSERTATION

Test of the Pauli Exclusion Principle for electrons in the Gran Sasso underground laboratory

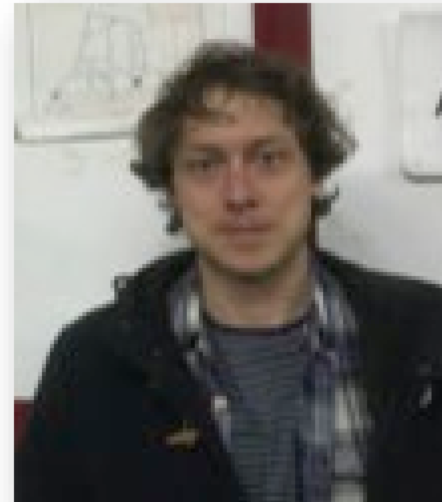
at the Stefan Meyer Institute for subatomic physics

under the supervision of
Priv.-Doz. Dr. Johann Marton

by
Andreas Pichler
Keramikstrasse 459,
3511 Furth

February 20, 2018

signature student



Andreas Pichler
PhD Student
Associated to DK-PI
Finished April 2018
with distinction

Now PostDoc in the framework of the FWF project

The experiment VIP (VIP2) on the Pauli Exclusion Principle for electrons - and thus the spin statistics connection - takes place in the Gran Sasso underground laboratory. This talk will discuss the experimental method and will review the work and results. The current status and an outlook of the planned studies in order to reach highest sensitivity will be given.

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DISCRETE18

SYMPOSIUM ON PROSPECTS IN THE PHYSICS OF DISCRETE SYMMETRIES

26-30 NOVEMBER 2018
AUSTRIAN ACADEMY OF SCIENCES, VIENNA

Recent Publications (selected)

H. Shi, E. Milotti, J. Marton, A. Pichler, et al.
Experimental search for the violation of Pauli Exclusion Principle.
European Physics Journal C, 78(4):319, 2018

C. Curceanu, J. Marton, D. Budker et al.
Putting the Pauli exclusion principle on trial
Cern Courier, March 2018

A. Pichler
Test of the Pauli Exclusion Principle for electrons i
underground laboratory
PhD Thesis, 2018

C. Curceanu, H. Shi, J. Marton, A. Pichler, et al.
Test of the Pauli Exclusion Principle in the VIP-2 Underground Experiment.
Entropy, 19(7):300, 2017

J. Marton, chapter "Underground Test of Quantum Mechanics: The VIP2 Experiment" in A. Khrennikov, Quantum Foundations, Probability and Information, Springer, 2018 in press.