ÖAW AUSTRIAN ACADEMY OF SCIENCES

The VIP2 at LNGS: Search for Pauli-forbidden atomic transitions

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ÖAW-Vienna

Workshop Quantum Foundations
New Frontiers in Testing Quantum Mechanics from Underground to the Space
29 Nov – 1Dec, 2017

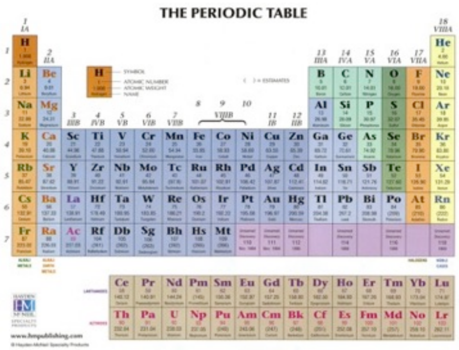
https://www.lngs.infn.it/en/pagine/vip-eng

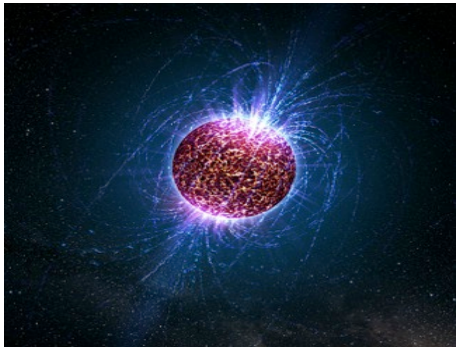
FWF Project P25529-N20

John Templeton Foundation

Outline

- PEP - a solid rule of nature (i.e. pillar of QM)
- Experiments testing PEP
- Experimental methods of VIP2
- Results obtained
- Summary and outlook





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

Fundamentals

For identical particles observable results should be independent on the particle labelling.

Symmetry in Permutation: observables are unchanged under permutation of the identical particle labels. Symmetry – no change in time.

Transitions between states of different permutation symmetry → forbidden (Messiah-Greenberg Superselection rule)

$$\langle \Psi_1 | \hat{V} | \Psi_2 \rangle = 0$$

The Pauli Principle and the spin statistics

Ralph Kronig (1904-1995) suggested that electrons have spin (1925).
Pauli: *"it is indeed a very clever idea but has nothing to do with reality"*

Our Knowledge today:
Bosons and Fermions
Symmetric states → bosons (possibly many particles in the same quantum state)
Anti-symmetric states → fermions (one particle per quantum state)
→ Different statistics

OCTOBER 15, 1940 PHYSICAL REVIEW VOLUME 58

The Connection Between Spin and Statistics[1]

W. PAULI
Physikalisches Institut, Eidg. Technischen Hochschule, Zürich, Switzerland and Institute for Advanced Study, Princeton, New Jersey

(Received August 19, 1940)

In the following paper we conclude for the relativistically invariant wave equation for free particles: From postulate (I), according to which the energy must be positive, the necessity of *Fermi-Dirac* statistics for particles with arbitrary half-integral spin; from postulate (II), according to which observables on different space-time points with a space-like distance are commutable, the necessity of *Einstein-Bose* statistics for particles with arbitrary integral spin. It has been found useful to divide the quantities which are irreducible against Lorentz transformations into four symmetry classes which have a commutable multiplication like $+1$, -1, $+\epsilon$, $-\epsilon$ with $\epsilon^2=1$.

Hence we come to the result: *For integral spin the quantization according to the exclusion principle is not possible. For this result it is essential, that*

PR
200 citations
The Connection Between Spin and Statistics
W. Pauli, Phys. Rev. **58**, 716 (1940) – Published 15 October 1940
Show Abstract

In conclusion we wish to state, that according to our opinion the connection between spin and statistics is one of the most important applications of the special relativity theory.

From Ian Duck and E.C.G. Sudarshan, Am.J.Phys. 66 (1998) 284pp

This paper is our response to a question raised by Neuenschwander in the "Questions and Answers" section of The American Journal of Physics,[1] whom we quote:

> "In the *Feynman Lectures on Physics*, Richard Feynman said: 'Why is it that particles with half-integral spin are Fermi particles whose amplitudes add with the minus sign, whereas particles with integral spin are Bose particles whose amplitudes add with the positive sign? We apologize for the fact that we cannot give you an elementary explanation. An explanation has been worked out by Pauli from complicated arguments of quantum field theory and relativity. He has shown that the two must necessarily go together, but we have not been able to find a way of reproducing his arguments on an elementary level.... This probably means that we do not have a complete understanding of the fundamental principle involved... .'
>
> Has anyone made any progress toward an 'elementary' argument for the Spin-Statistics Theorem?"

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

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)

PHYSICAL REVIEW D 78, 126009 (2008)

Spin-statistics violations in superstring theory

Mark G. Jackson*
Particle Astrophysics Center and Theory Group, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
(Received 28 October 2008; published 29 December 2008)

Experimental constraints

-Energy scale → high energy experiments

-Coupling constant → precision experiments
(like deviations from fermionic spin statistics)

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

VIP 2006

This bound is expected to improve another 2 orders of magnitude over the next few years due to larger integrated currents. Though the energy scale is low at only 8 keV, the incredible precision means this might be a viable way of detecting superstring-motived violations.

The parameter “β ”

Ignatiev & Kuzmin model — creation and destruction operators connect 3 states

- the vacuum state $|0>$
- the single occupancy state $|1>$
- the non-standard double-occupancy state $|2>$

through the following relations:

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

The parameter β quantifies the degree of violation in the transition $|1> \rightarrow |2>$. It is very small and for β→0 we can have the Fermi - Dirac statistic again.

Why the special interest in validity in the leptonic sector ?

Violation of the spin-statistics relation would have an important impact not only on microscopic atomic, nuclear, and particle physics scales, but also induce very interesting effects at astronomically large scales. In particular, it was argued that spin-statictics relation for neutrinos could be strongly violated, If so, neutrino may be the sole dark matter particle, contributing both to hot and cold dark matter.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Physics Letters B 621 (2005) 1–10

PHYSICS LETTERS B

www.elsevier.com/locate/physletb

Possible violation of the spin-statistics relation for neutrinos: Cosmological and astrophysical consequences

A.D. Dolgov [a,b,c], A.Yu. Smirnov [c,d]

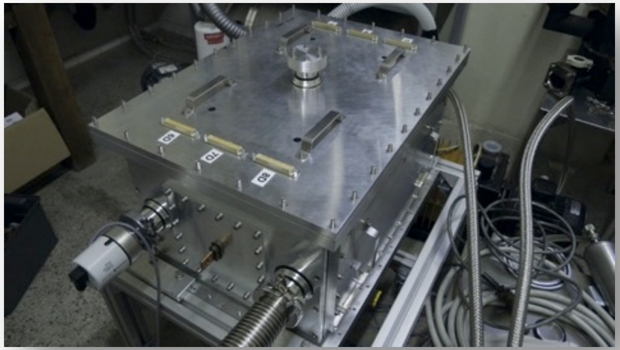
There are speculations concerning a bosonic component of neutrinos wit h severe cosmological consequences (A. Dolgov et al.)

Motivation for experimental tests

- PEP a solid rule of nature but no intuitive explanation (Pauli)
- PEP connected with spin statistics
- Spin statistics connection is a very robust feature of quantum field theory
- Nature is divided in fermions and bosons

- VIP/VIP-2 idea: testing PEP for electrons employing the method of Ramberg-Snow with detectors successfully used in kaonic atom spectroscopy (x-ray detector arrays, CCDs, SDDs)

If something in fundamental physics can be tested, then it absolutely must be tested (L. Okun)



Theories of Violation of Statistics

General principles of quantum theory DO NOT require that all particles are either bosons or fermions – the restrict

… the explanation of the spin–statistics connection by Fierz and by Pauli in the late 1930s, and by Luders and Zumino and by Burgoyne in the late 1950s, ranks as one of the great triumphs of relativistic quantum field theory. (Zee, 2010: 121)

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"We note that all the proofs are *negative proofs*: integral spin fields cannot satisfy anti-commuting Fermi Dirac statistics; half-integral spin fields cannot satisfy commuting Bose-Einstein statistics."

I. Duck and E.C.G. Sudarshan, Pauli and the Spin-Statistics Theorem, World Scientific, 1997, p.487.

Several attempts to violate Spin-Statistics:

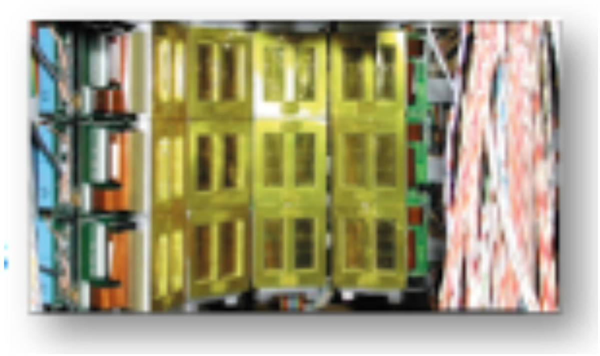
- Parastatistics → large effect, ruled out
- Ignatiev-Kuzmin →negative squared norm states
- Quon theory → spacelike commutativity fails
- Superstring theory (c.f. M. Jackson) → energy scale?

Experimental tests

Many experimental tests are spin-off studies of experiments designedfor different topics like dark matter, neutrino physics

In the case of VIP/VIP2 CCD/SDD X-ray detectors available - developed for exotic atom spectroscopy at LNF-DAFNE

VIP . CCDs



VIP2 . SDDs

Experimental tests

◆ Atomic transitions	$< 6.5 \times 10^{-46}$
◆ Nuclear transitions	$< 7.4 \times 10^{-60}$
◆ Nuclear reactions	
◆ PEP-forbidden nuclear structures	$< 5 \times 10^{-33}$
◆ PEP forbidden atomic structures	$< 4 \times 10^{-17}$
◆ Neutrino statistics	
◆ Astrophysics and cosmology	$< 2 \times 10^{-28}$

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

PEP Tests with 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

Experiment of Goldhaber & Scharff-Goldhaber

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

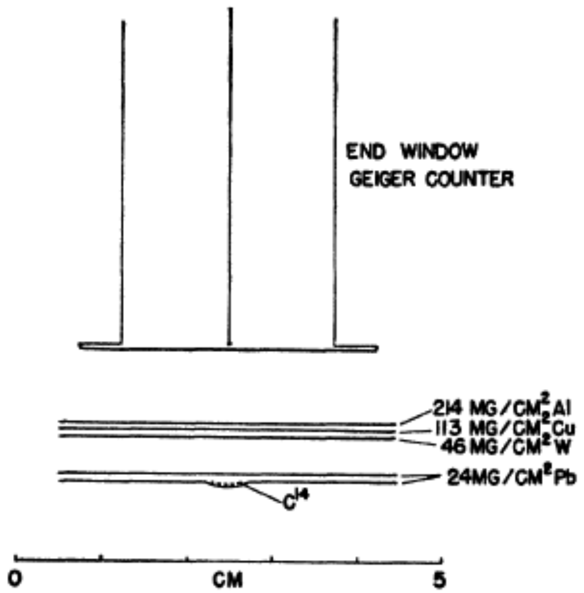
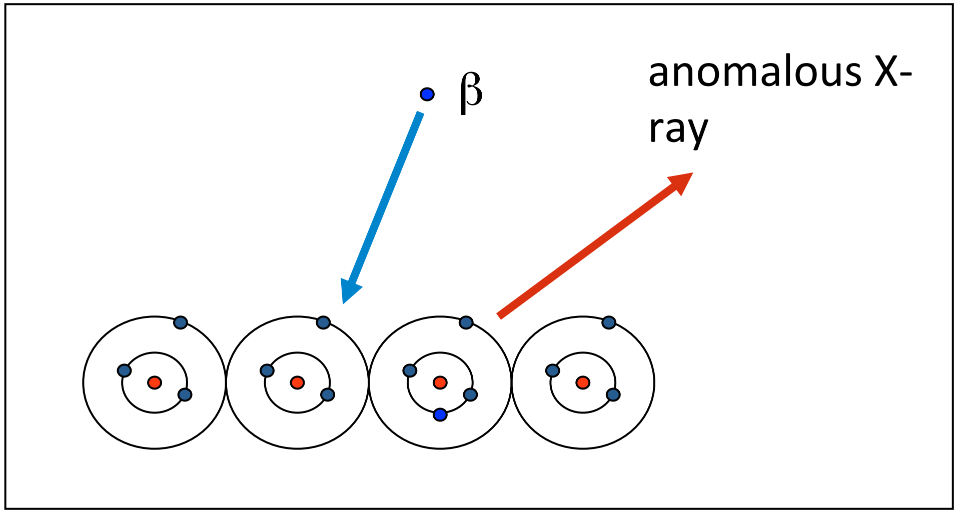
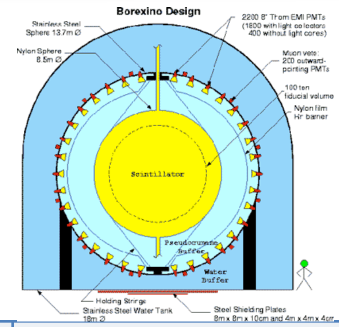


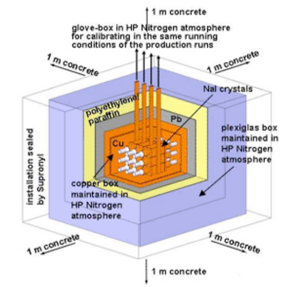
FIG. 1. Arrangement used in search for photons from beta-rays stopped in lead.

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



Best limits for PEP Violation





Simplified schema of ~ 100 kg NaI(Tl) set-up

Nuclear transition	$^{12}C \rightarrow {}^{11}B + p$	BOREXINO @LNGS	$\frac{\beta^2}{2} < 7.4 \cdot 10^{-60}$	G. Bellini et al., PRC 81 (2010) 034,317
Atomic transition	$I \rightarrow I + \gamma$	DAMA @LNGS	$\frac{\beta^2}{2} < 4.7 \cdot 10^{-46}$	R. Bernabei et al., Eur. Phys. J. C62 (2009) 327

PHYSICAL REVIEW C **81**, 034317 (2010)

New experimental limits on the Pauli-forbidden transitions in ^{12}C nuclei obtained with 485 days Borexino data

G. Bellini,[1] S. Bonetti,[1]
L. Ludhova,[1] E. Meroni,[1]
F. Calaprice,[4] A. Chavarr
J. Xu,[4] C. Carraro,[5] S. D
S. Zavatarelli,[5] H. de Ker
I. Machulin,[8] A. Sabelni
S. Gazzana,[10] C. Ghiano,[10] Aldo Ianni,[10] G. Korga,[10] D. Montanari,[10] A. Razeto,[10] R. Tartaglia,[10] M. Goeger-Neff,[11] T. Lewke,[11] Q. Meindl,[11] L. Oberauer,[11] F. von Feilitzsch,[11] Y. Winter,[11] M. Wurm,[11] C. Grieb,[12] S. Hardy,[12] M. Joyce,[12] S. Manecki,[12] L. Papp,[12] R. S. Raghavan,[12] D. Rountree,[12] R. B. Vogelaar,[12] W. Maneschg,[13] S. Schönert,[13] H. Simgen,[13] G. Zuzel,[13] M. Misiaszek,[14] M. Wojcik,[14] F. Ortica,[15] and A. Romani[15]
(Borexino Collaboration)

However: Stable system transitions !

Nuclear Physics in Astrophysics IV — IOP Publishing
Journal of Physics: Conference Series **202** (2010) 012039 — doi:10.1088/1742-6596/202/1/012039

...Exclusion

...J. Dai[6],
A. d'Angelo[5,4], H.L. He[6], A. Incicchitti[4], H.H. Kuang[6], X.H. Ma[6],
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[8] *University of Jing Gangshan, Jiangxi, China*

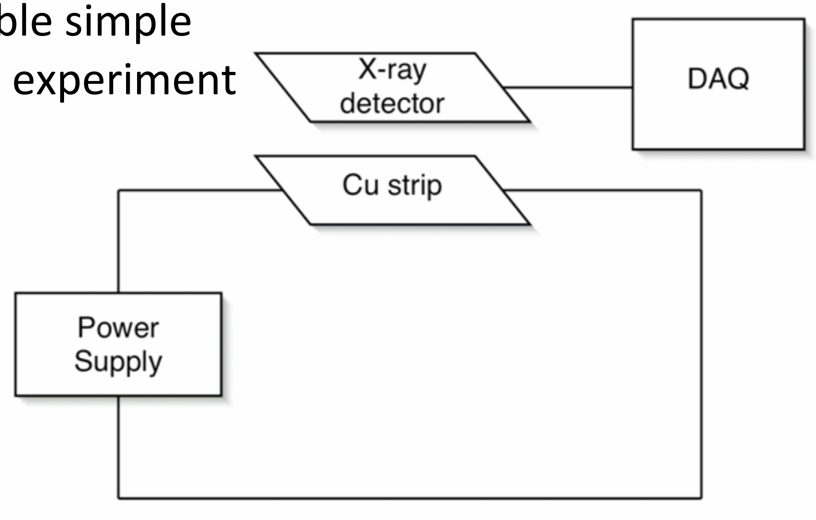
Abstract. Searches for non-paulian nuclear processes, i.e. processes normally forbidden by the Pauli–Exclusion–Principle (PEP) with highly radiopure NaI(Tl) scintillators allow the test of this fundamental principle with high sensitivity. Status and perspectives are briefly addressed.

Process	Type	Experimental limit	$\frac{1}{2}\beta^2$ limit	Note
Atomic transitions				
$\beta^- + \mathrm{Pb} \to \check{\mathrm{Pb}}$	Ia recently created fermions (electrons)		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 distant fermions (electrons)		1.7×10^{-26}	
$e^-_I + \mathrm{Cu} \to \check{\mathrm{Cu}}$	II		4.5×10^{-28}	VIP results
$e^-_I + \mathrm{Cu} \to \check{\mathrm{Cu}}$	II		6.0×10^{-29}	VIP results
$e^-_I + \mathrm{Pb} \to \check{\mathrm{Pb}}$	II		1.5×10^{-27}	S. R. Elliott et al., Found Phys (2012) 42:1015–1030
$e^-_f + \mathrm{Pb} \to \check{\mathrm{Pb}}$	IIa		2.6×10^{-39}	
$\mathrm{I} \to \check{\mathrm{I}} + $ X-ray	III	$\tau > 2 \times 10^{27}$ sec	3×10^{-44}	
$\mathrm{I} \to \check{\mathrm{I}} + $ X-ray	III	$\tau > 4.7 \times 10^{30}$ sec	6.5×10^{-46}	
		Stable system transition		
Nuclear transitions				
$^{12}\mathrm{C} \to ^{12}\tilde{\mathrm{C}} + \gamma$	III	$\tau > 6 \times 10^{27}$ y	1.7×10^{-44}	
$^{12}\mathrm{C} \to ^{12}\tilde{\mathrm{C}} + \gamma$	III	$\tau > 4.2 \times 10^{24}$ y		
$^{12}\mathrm{C} \to ^{12}\tilde{\mathrm{C}} + \gamma$	III	$\tau > 5.0 \times 10^{31}$ y	2.2×10^{-57}	BOREXINO
$^{12}\mathrm{C} \to ^{11}\tilde{\mathrm{B}} + p$	III	$\tau > 8.9 \times 10^{29}$ y	7.4×10^{-60}	Bellini, G., et al. (2010). Phys. Rev. C, 81(3), 034317

S. R. Elliott et al., Found Phys (2012) 42:1015–1030

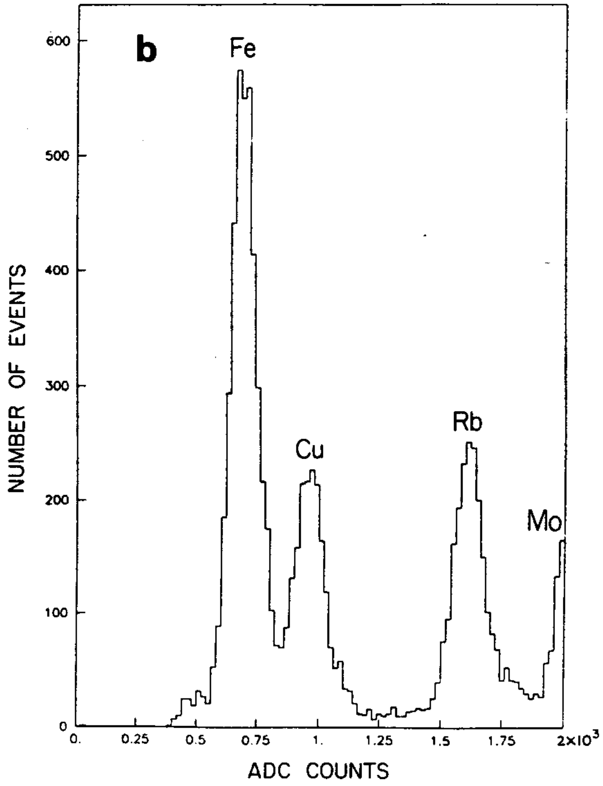
Ramberg & Snow experiment

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 .**

THE INTERNATIONAL VIP COLLABORATION

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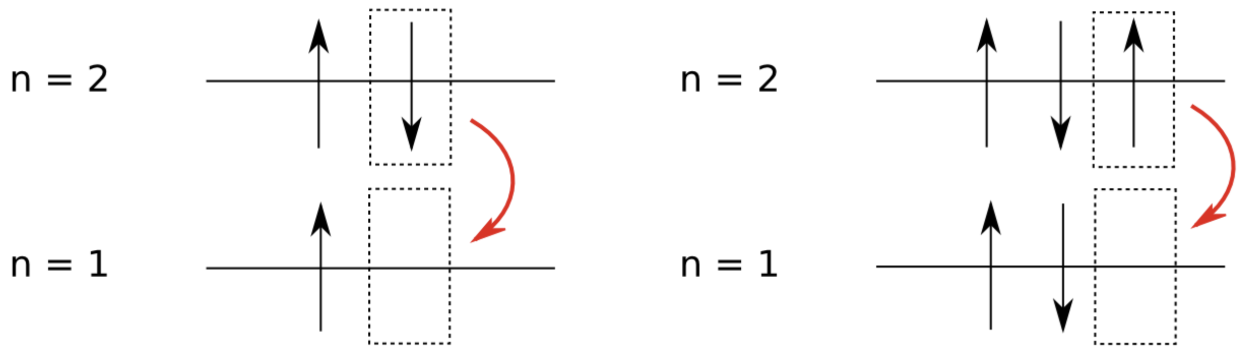
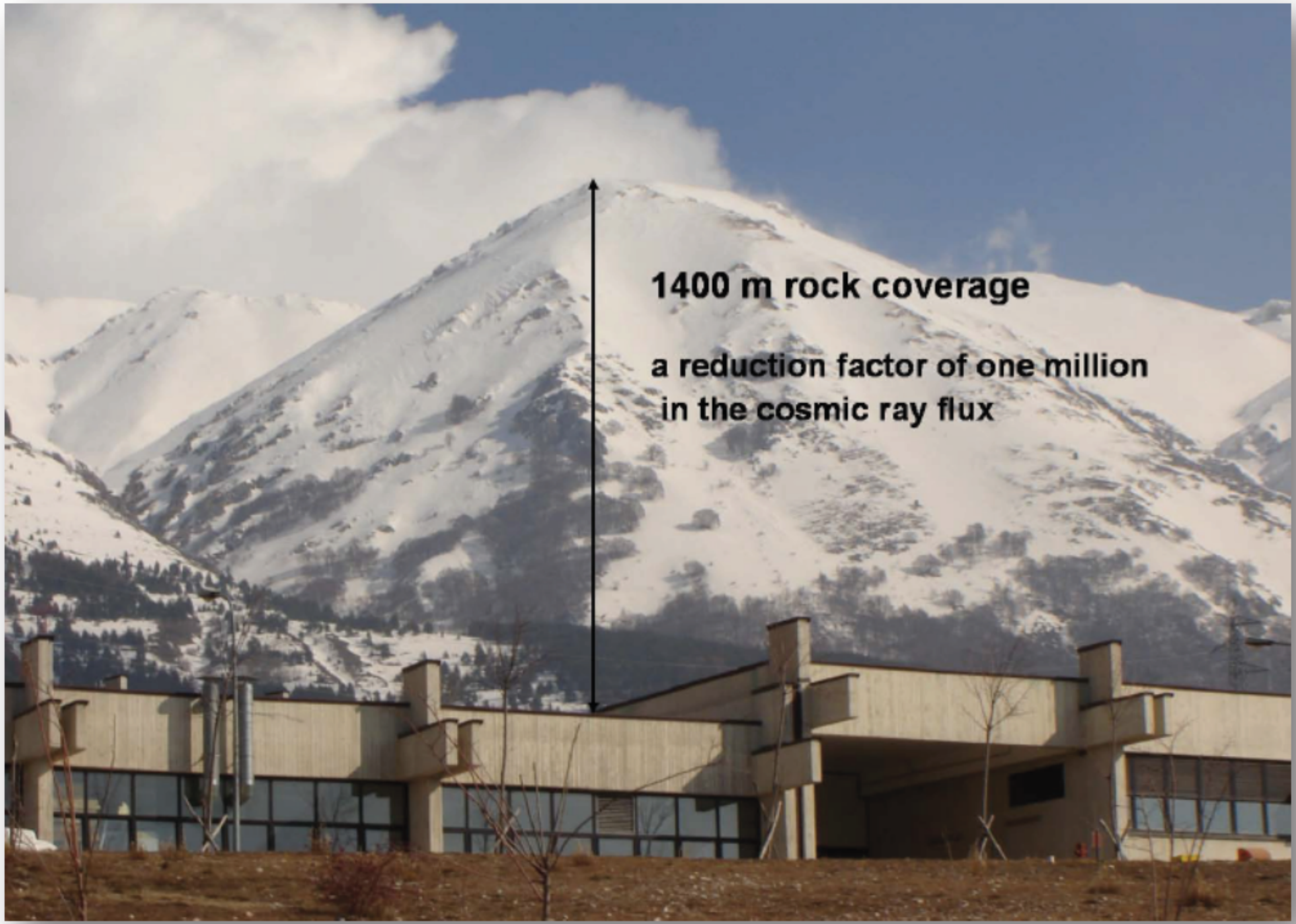
VIP Method: Improved Ramberg-Snow method: Introducing electrons via a current for probing

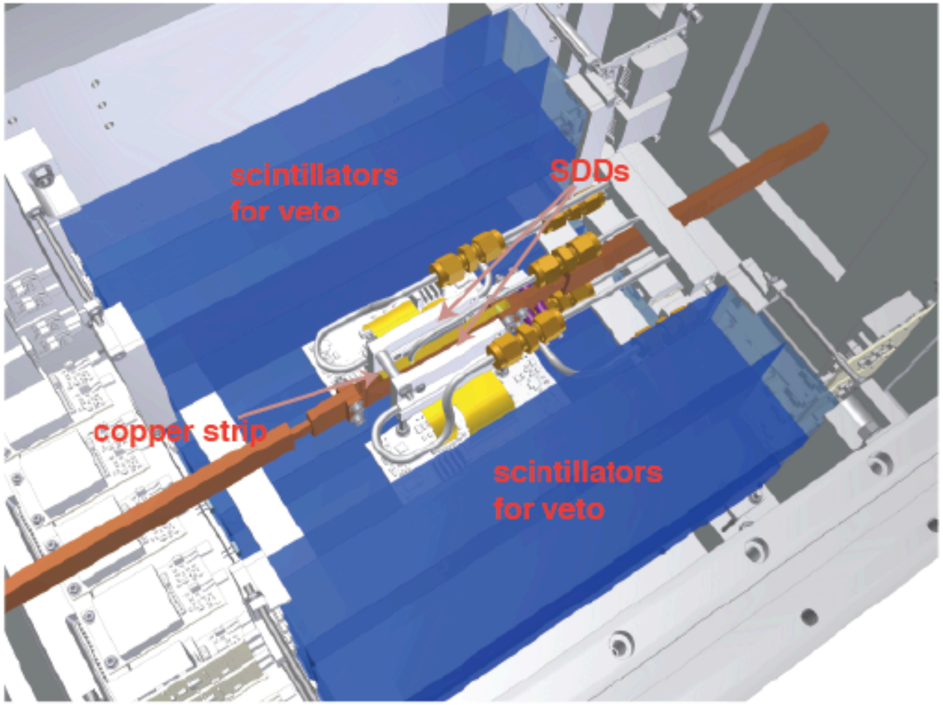
Search for anomalous X-ray transitions

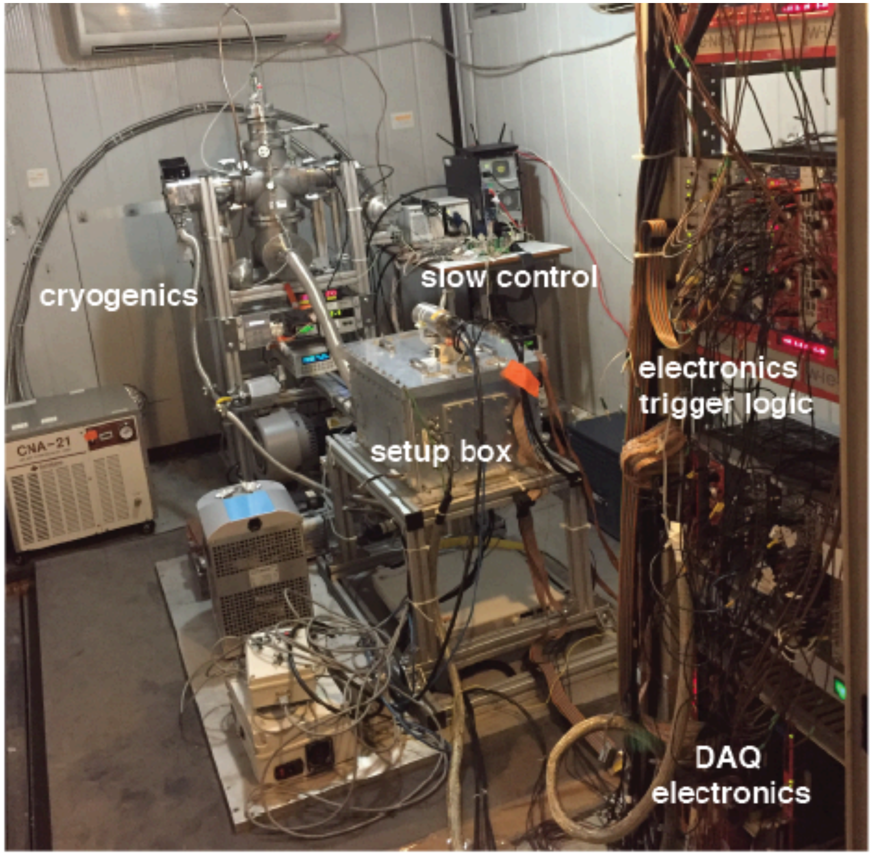


Normal 2p →1s transition	2p →1s transition violating Pauli principle
8.05 keV in Cu	**~ 7.7 keV in Cu**

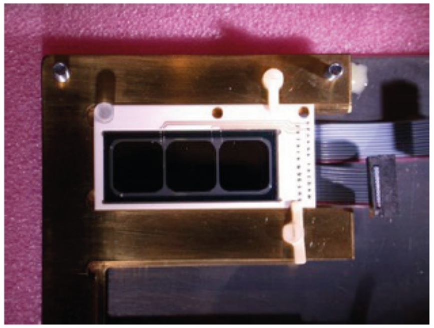

1400 m rock coverage
a reduction factor of one million
in the cosmic ray flux

VIP2 Installation at LNGS



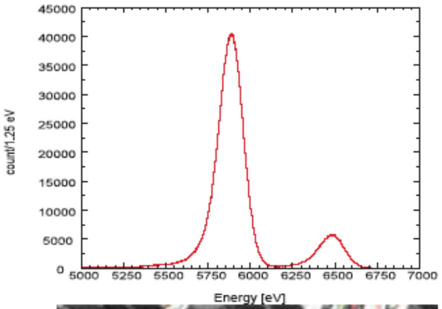


Improved experiment VIP2



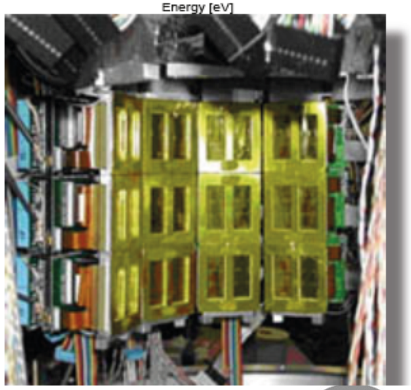
- Large (1 cm^2) SDDs provide excellent energy resolution (even superior than CCDs at 8keV)

- Timing capability for triggering



- Compact design suitable for gaining larger solid angle

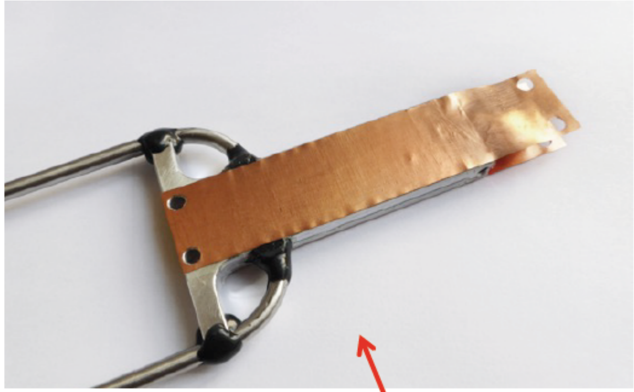
- Successfully used in the detection of kaonic atom x-ray spectroscopy at DAFNE (SIDDHARTA) with large background reduction

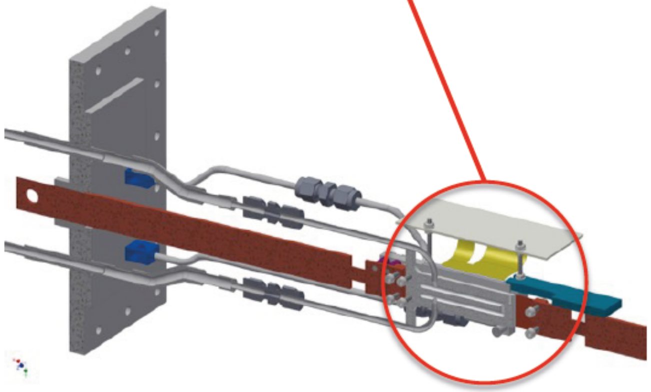


Copper target VIP2

Length: 30 mm
Width: 10 mm
Cross section: 0.4 mm^2

Current: 100 A

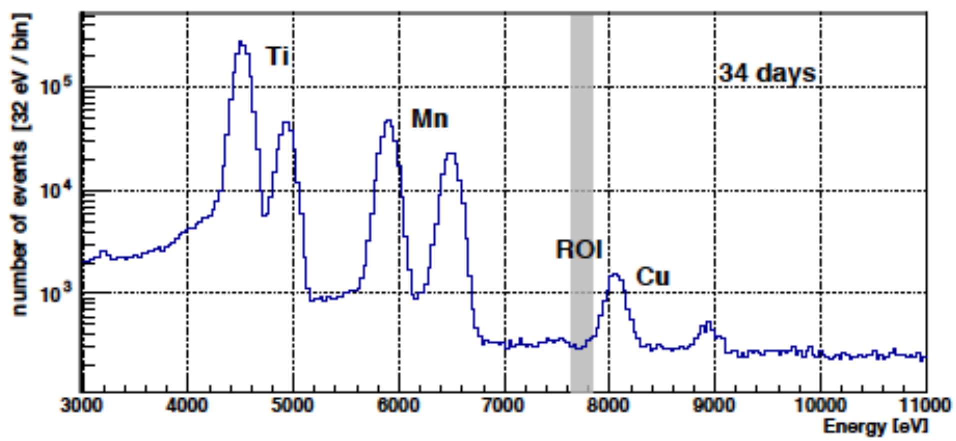




VIP-2 Data taking in2016

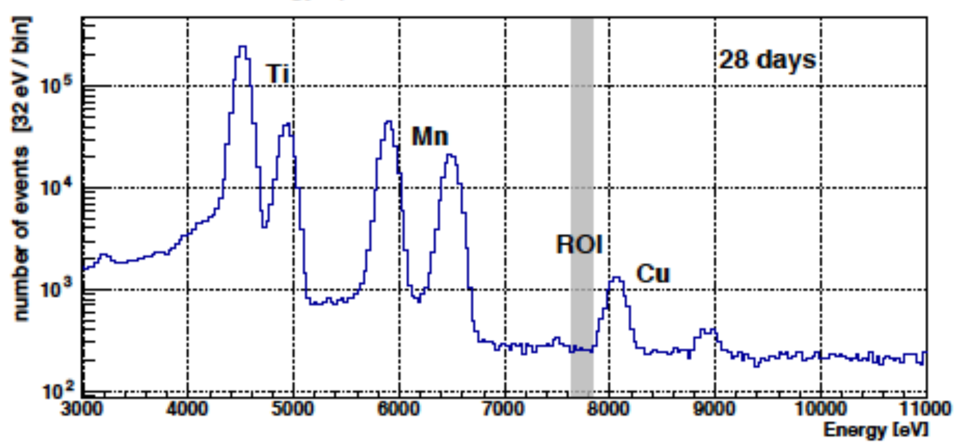
I = 100 A

Energy spectrum with **100 Ampere** current

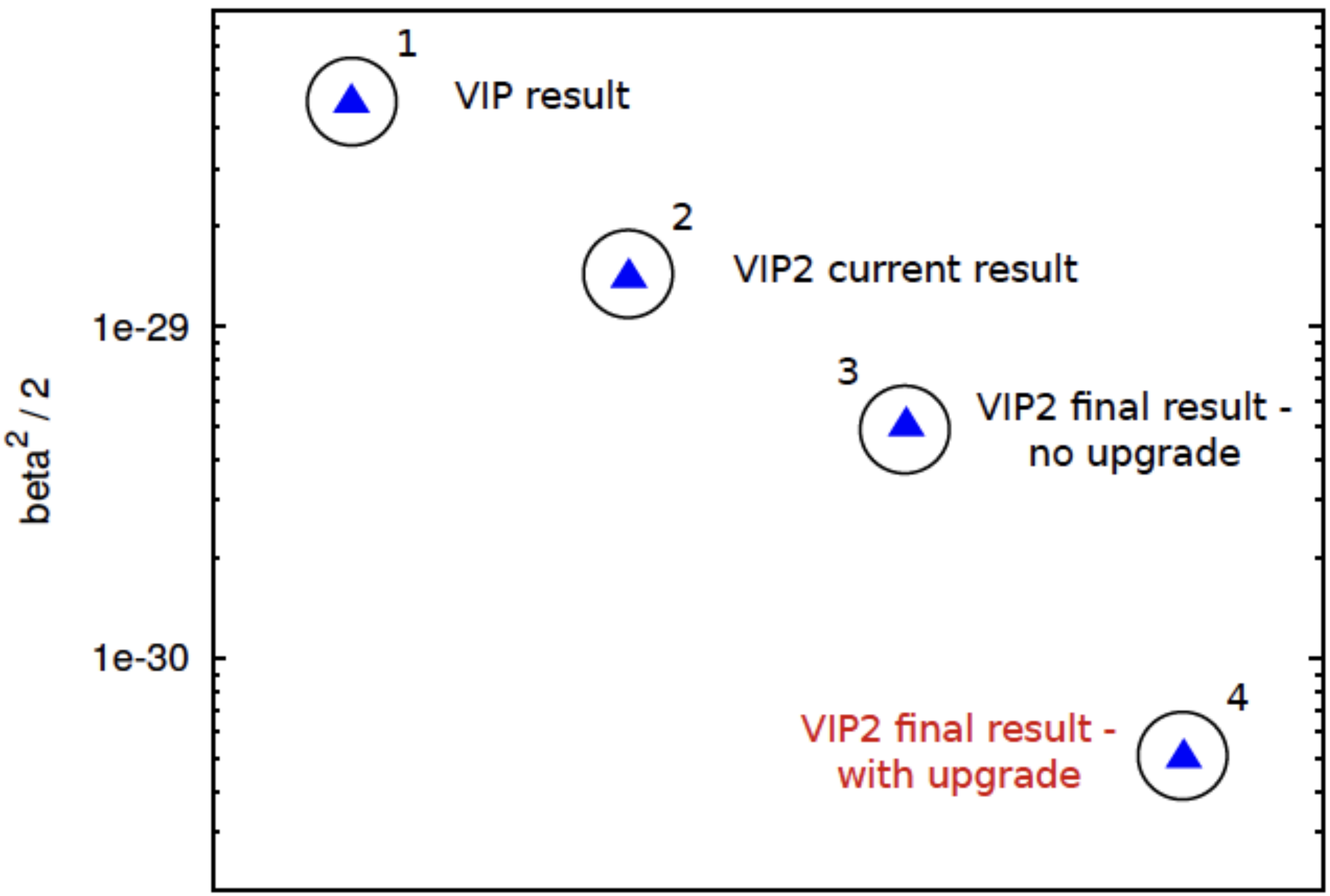


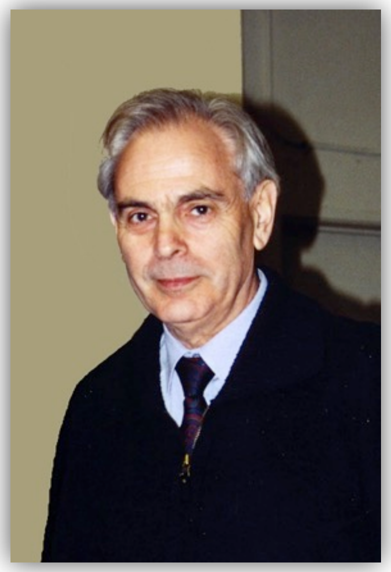
I = 0 A

Energy spectrum without current



Toward the final result





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 for your attention