Stefan Meyer Institute

Austrian Academy of Sciences

The Pauli Exclusion Principle for electrons – a high sensitivity test in the Gran Sasso underground laboratory

Johann Marton, SMI, Vienna
for the VIP Collaboration

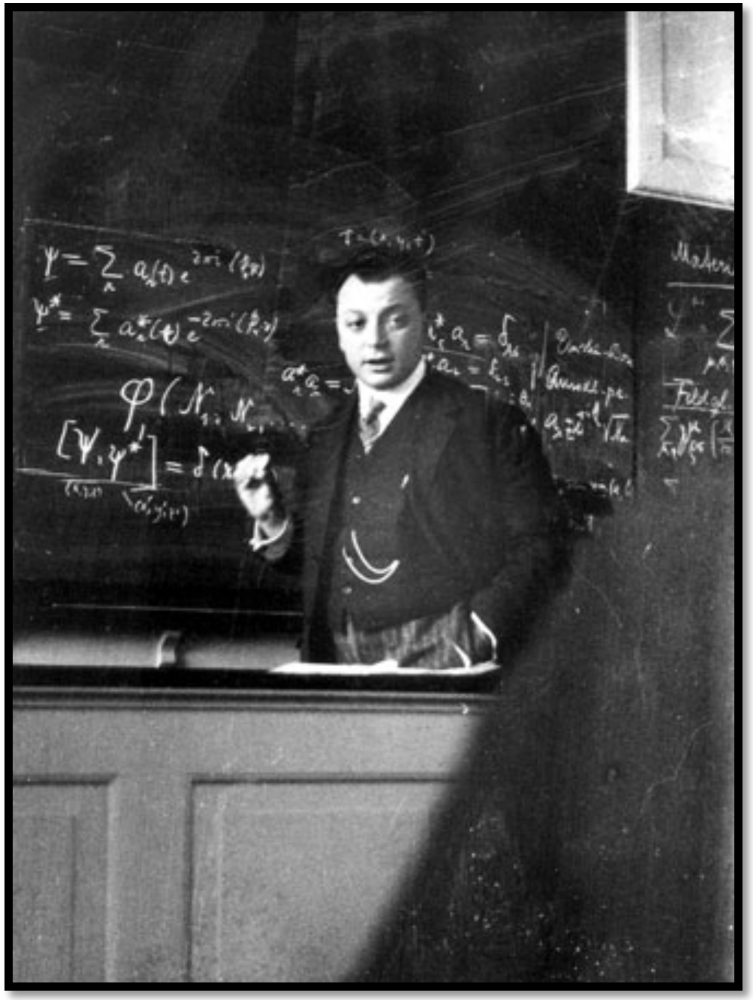
Outline

- Motivation
- Experimental Method
- Results
- Outlook to VIP2
- Summary

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.



Motivation

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

The Pauli Principle and the spin statistics

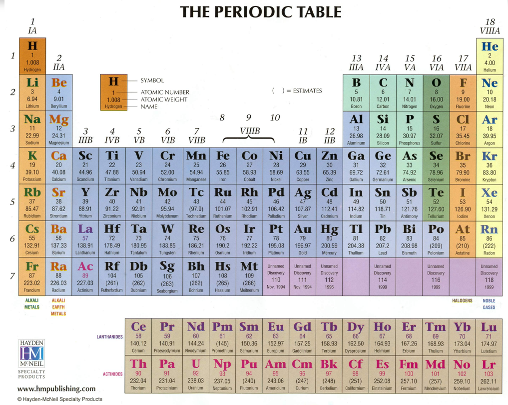
Ralph Kronig (1904-1995) suggested that electrons have spin (1925).
Pauli: “it is indeed a very clever idea but has nothing to do with reality”

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

Consequences

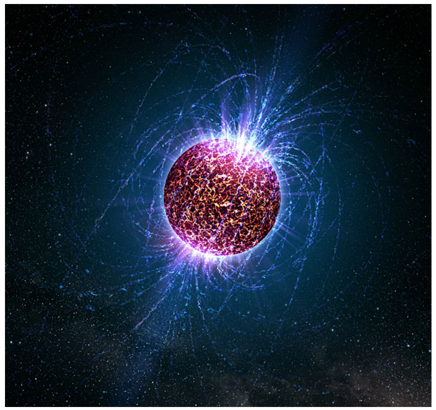
Some examples:

Periodic table of the elements



Stability of matter

Neutron stars



……

So far no violation of the spin-statistics could be found
- but violations can arise in string theory

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)

VIP 2006

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

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.

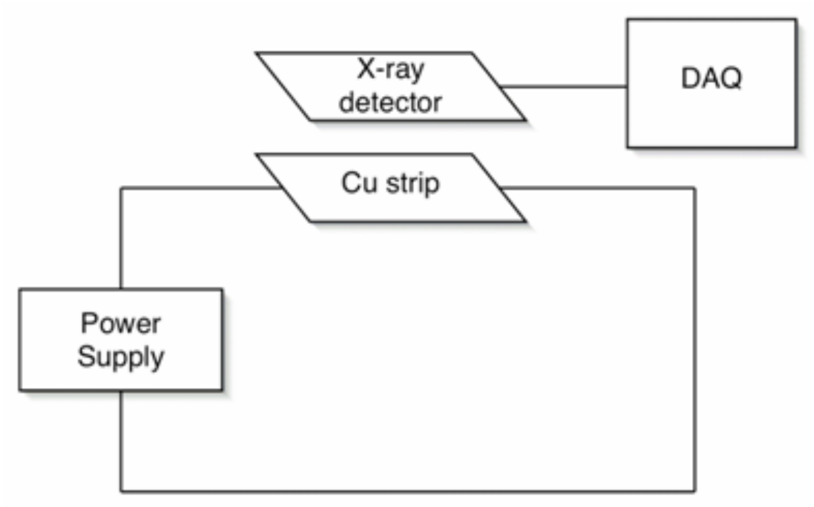
Methods to test PEP

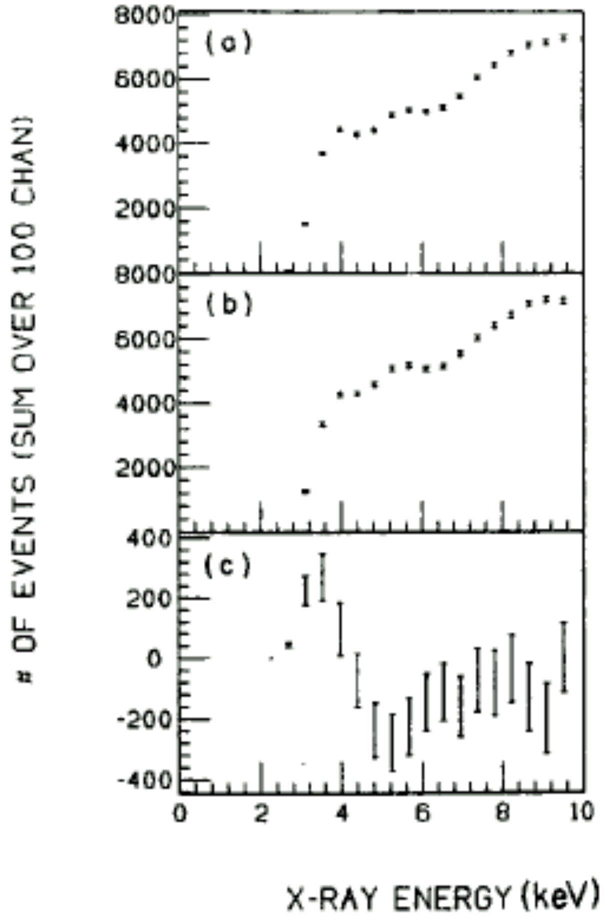
- Different methods – different assumptions
- Different systems, e.g. atoms, nuclei ...
- Clearest method: „new“ fermions testing PEP
- Avoiding Greenberg-Messiah superselection
- How to get „new“ fermions?
  - Radioactive source
  - Circulating current (Ramberg-Snow)
  - Pair production

The pre-VIP experiment limit

Ramberg and Snow (RS)

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





$$N_X \geq \beta^2 \left(0.90 \cdot 10^{28}\right)$$

$$\beta^2 / 2 \leq 1.7 \cdot 10^{-26} (> 95\% C.L.)$$

PEP Tests for electrons

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

Best limits for PEP Violation

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

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)

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

But: Stable system transitions !

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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.

Goal of VIP (**VI**olation of the **P**auli Principle)

The VIP experiment has the scientific goal of reducing by four orders of magnitude the limits on the probability of a possible violations of the Pauli exclusion principle for the electrons

From:

(Ramberg & Snow -1990)

$$\beta^2 / 2 \leq 1.7 \cdot 10^{-26} (> 95\% \;\; C.L.)$$

to

$$\beta^2 / 2 \leq 10^{-30}$$

THE INTERNATIONAL VIP COLLABORATION

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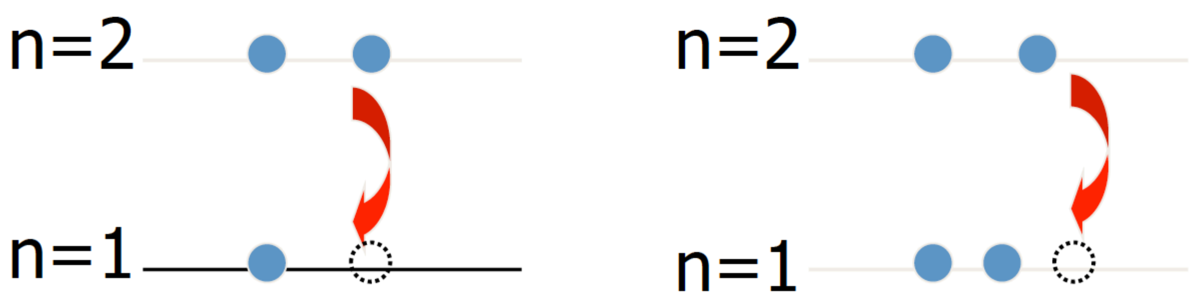
VIP Method: Improved Ramberg-Snow method: Introducing electrons via a current for probing

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

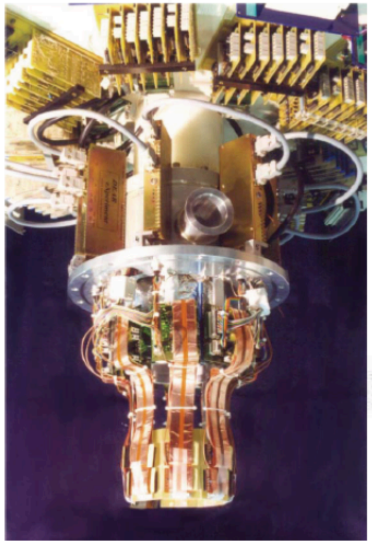
Transition energies of anomalous X-rays in Cu

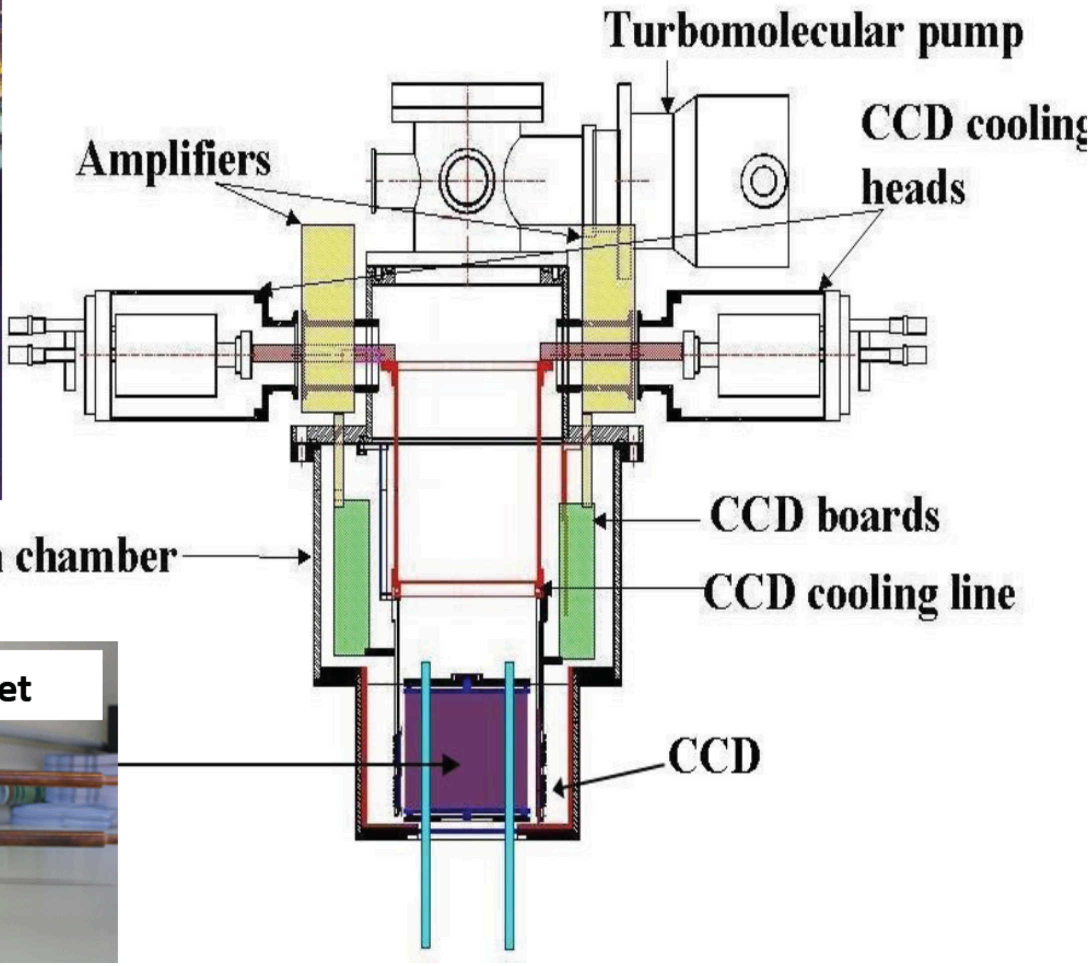
Multiconfiguration Dirac-Fock approach
(including rel. corrections, lamb shift, Breit operator, radiative corrections)

Transition	Initial en.	Final en.	Transition energy (eV)	Radiative transition rate (s-1)	Multipole order	
$2p_{1/2} - 1s_{1/2}$	-45799	-53528	7729	2.63E+14	E1	K_α
$2p_{3/2} - 1s_{1/2}$	-45780	-53528	7748	2.56E+14	E1+M2	
$3p_{1/2} - 1s_{1/2}$	-44998	-53528	8530	2.78E+13	E1	K_β
$3p_{3/2} - 1s_{1/2}$	-44996	-53528	8532	2.68E+13	E1+M2	

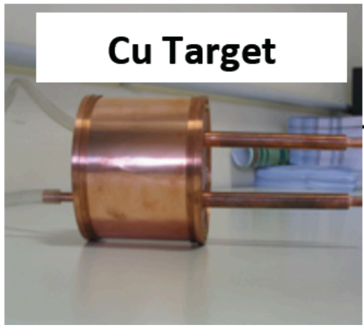
"Normal" 2p-1s transition in Cu @ 8040 eV → ~ 300 eV difference in energy, experimentally resolvable

VIP Apparatus





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



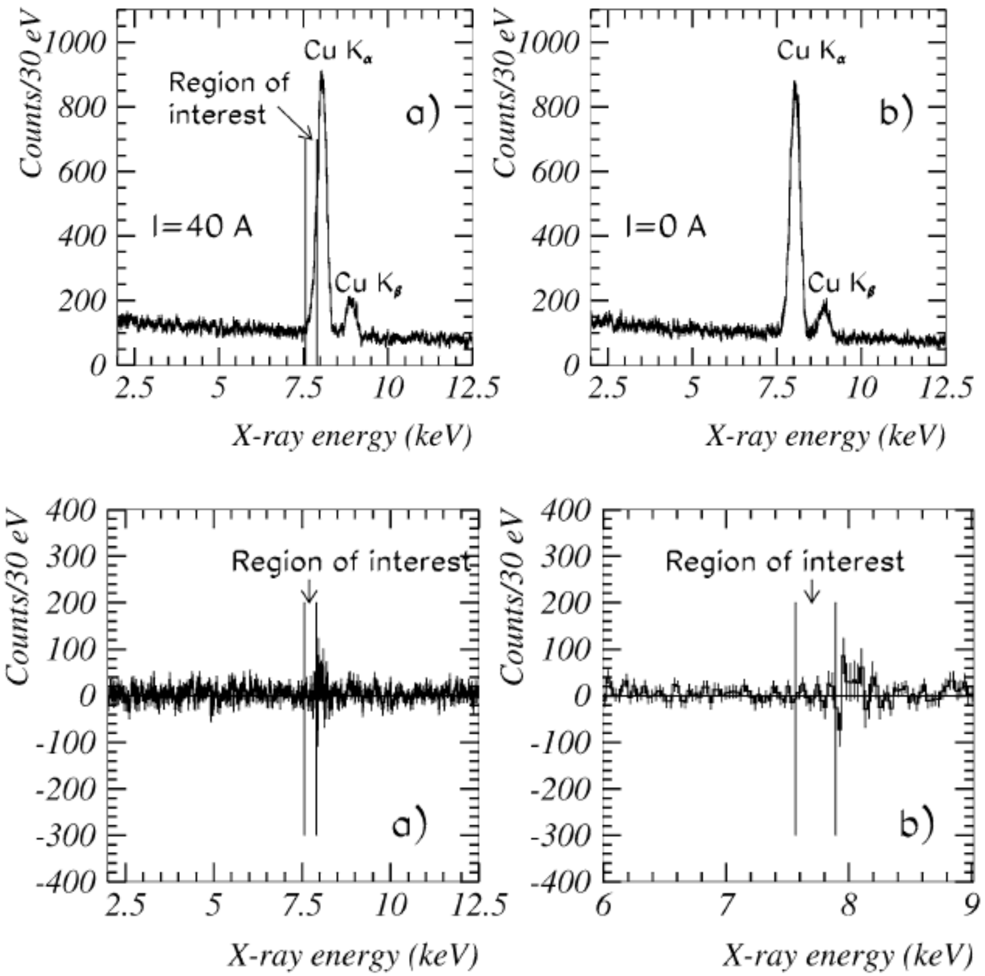
X-ray spectra with the VIP final setup at LNF

2 types of measurements:

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

Subtraction gives:

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



Analysis of VIP with RS method:

$$\int_T I(t)dt = 34.824\cdot 10^6 C$$

$$D = 0.088m$$

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

$$\rho = 8.96\cdot 10^3 kg\cdot m^{-3}$$

$$f_g \approx 0.01$$

$$\Delta N_X \geq \frac{1}{2}\beta^2 N_{new}\frac{N_{\text{int}}}{10} f_g = \frac{\beta^2(\Sigma I\Delta t)D}{e\mu}\frac{1}{20} f_g$$

$$\Delta N_X \geq \frac{\beta^2}{2}\left(4.9\cdot 10^{29}\right)$$

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

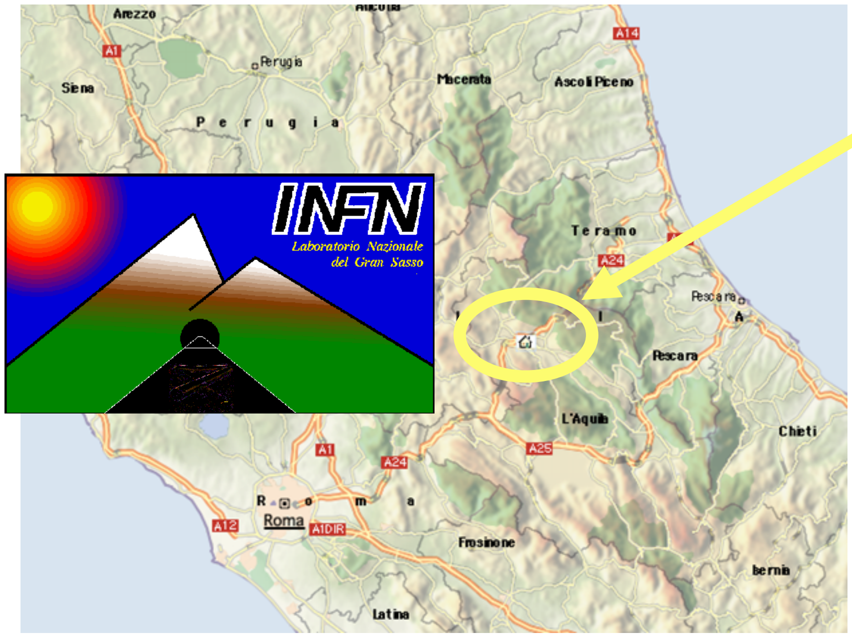
$$\frac{\beta^2}{2} \leq \frac{3\cdot 73}{4.9\cdot 10^{29}}$$

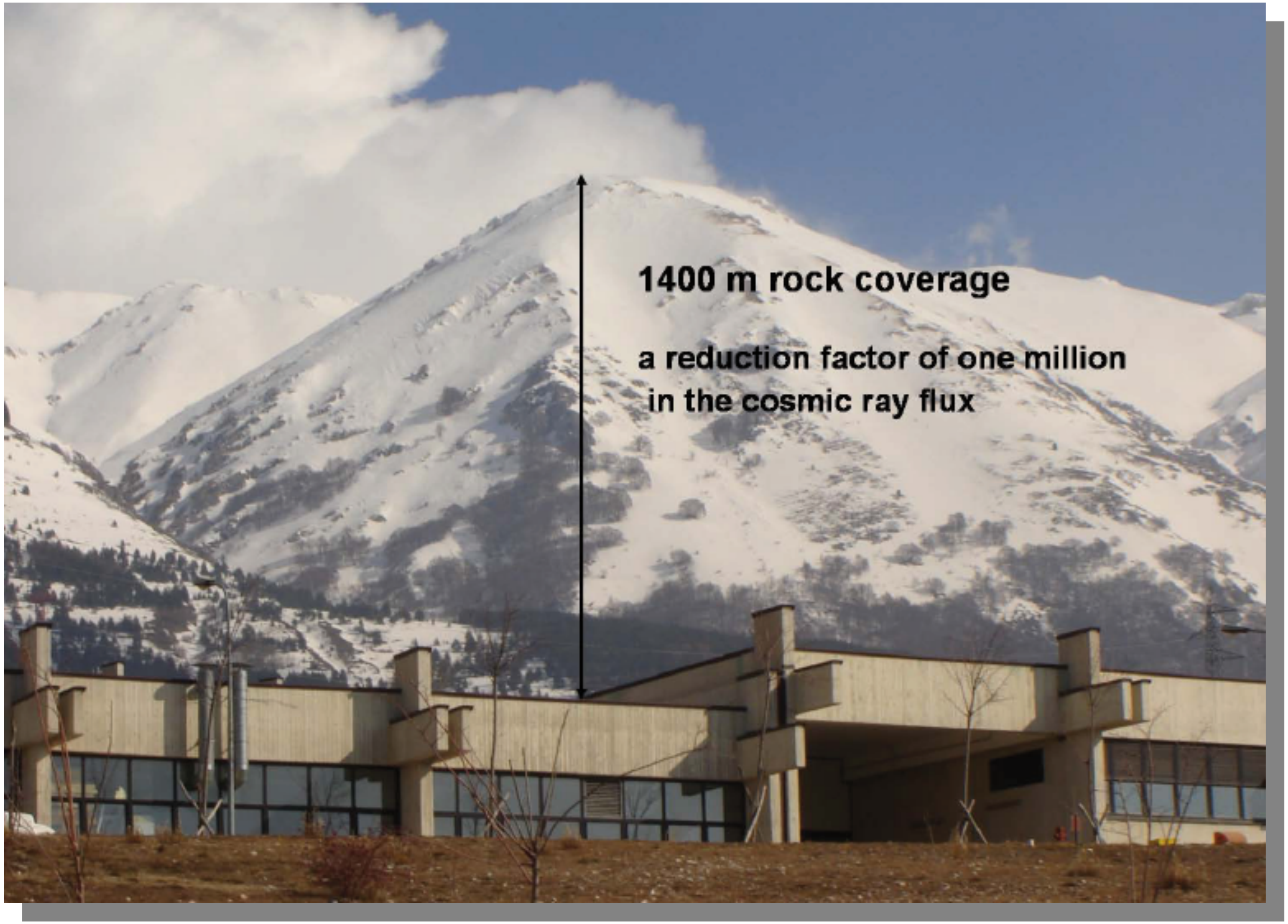
$$\frac{\beta^2}{2} \leq 4.5\cdot 10^{-28} \;\; at\, 99.7\, C.L.$$

Test site and final location:

Laboratori Nazionali del Gran Sasso (LNGS), Istituto Nazionale di Fisica Nucleare

LNGS




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


VIP Experiment at LNGS Thu Apr 13 2006 12:19:35

VIP-LNGS result

After about 2 years running

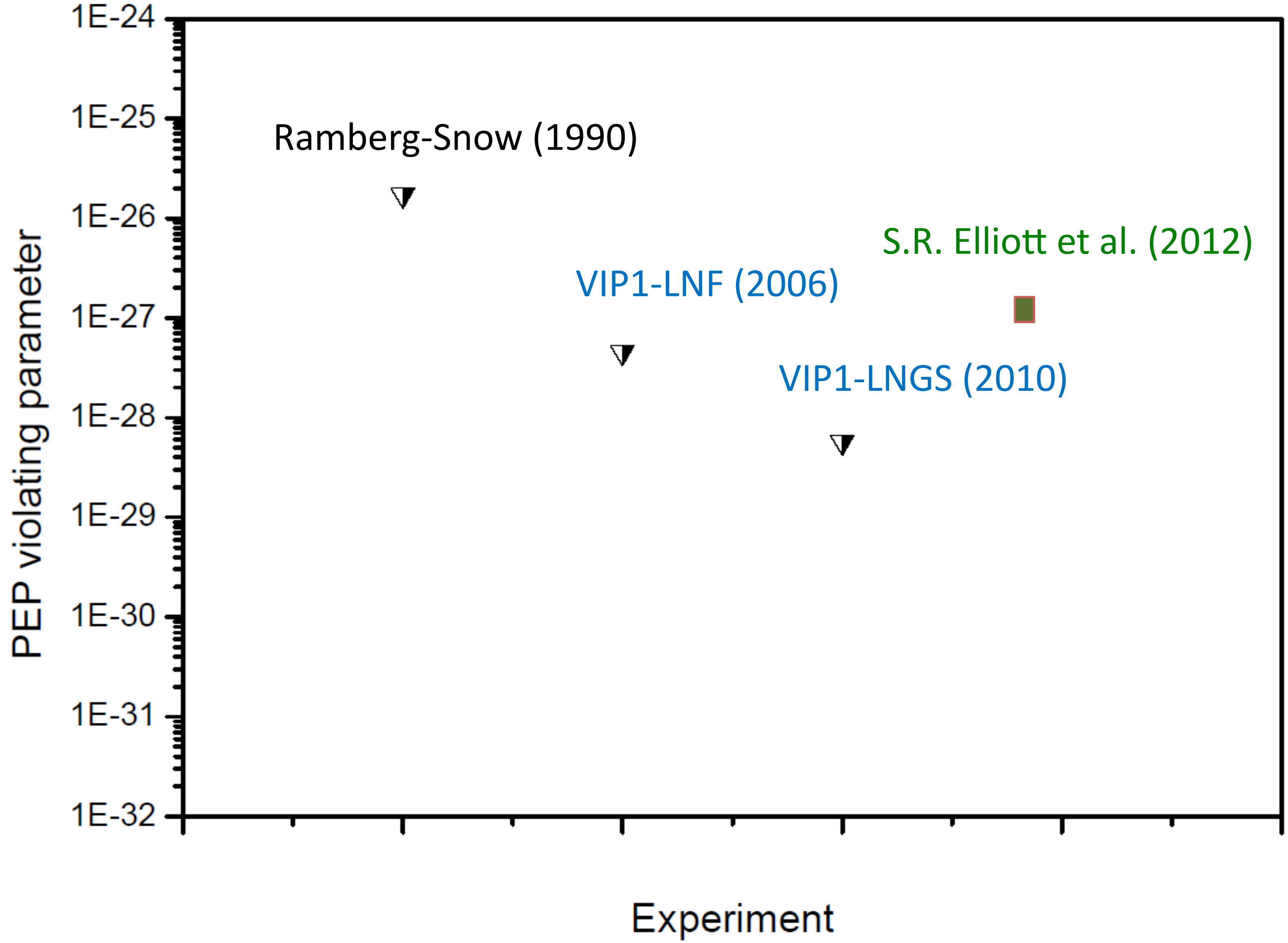
$$\beta^2/2 < 4.7 \times 10^{-29}$$

(Preliminary)

L. Sperandio Ph. D. Thesis, Univ. Roma2, 2008
S. Bartalucci *et al.,* AIP Conf. Proc. 1232, ed. A.Yu. Khrennikov, 206

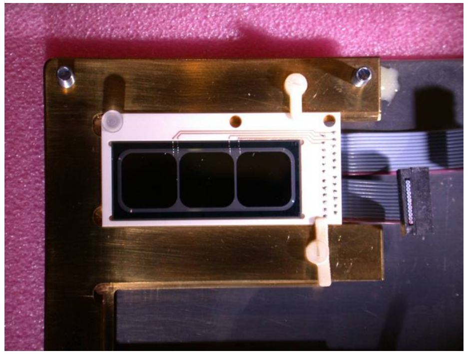
Experiments testing PEP using "fresh" electrons

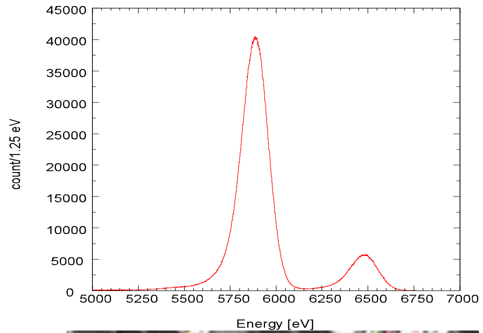
Experiment	Year	Material	Limit	Source	Publication
M. Goldhaber, G. Scharff Goldhaber	1948	Pb	$3 \cdot 10^{-2}$	electrons from β^- decay	PR 73 (1948) 1492
E. Ramberg, G.A. Snow	1990	Cu	$1{,}7 \cdot 10^{-26}$	electric current	PLB 238 (1990) 438
S. Bartalucci et al. (VIP)	2006	Cu	$4{,}5 \cdot 10^{-28}$	electric current	PLB 641 (2006) 18
C. Curceanu et al. (VIP)	2011	Cu	$4{,}7 \cdot 10^{-29}$	electric current	Phys. Proc. 17 (2011) 40
S.R. Elliott et al.	2012	Pb	$1{,}5 \cdot 10^{-27}$	electric current	arXiv:1107.3118v2

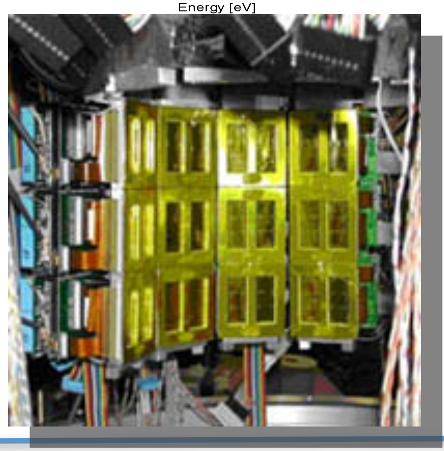

1E-24
1E-25
1E-26
1E-27
1E-28
1E-29
1E-30
1E-31
1E-32
PEP violating parameter
Ramberg-Snow (1990)
VIP1-LNF (2006)
S.R. Elliott et al. (2012)
VIP1-LNGS (2010)
Experiment

Improved experiment VIP2

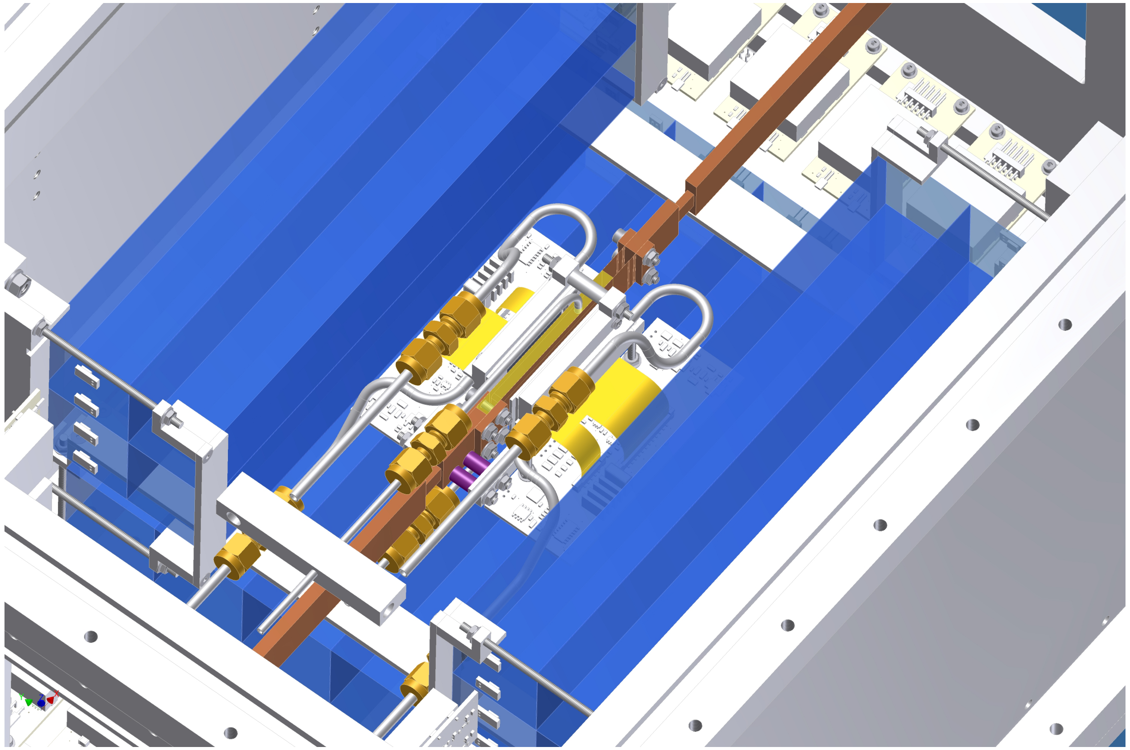
- Large (1 cm^2) SDDs provide excellent energy resolution (even superior than CCDs at 8keV)
- Timing capability for triggering
- Compact design suitable for gaining larger solid angle
- Successfully used in the detection of kaonic atom x-ray spectroscopy at DAFNE (SIDDHARTA) with large background reduction

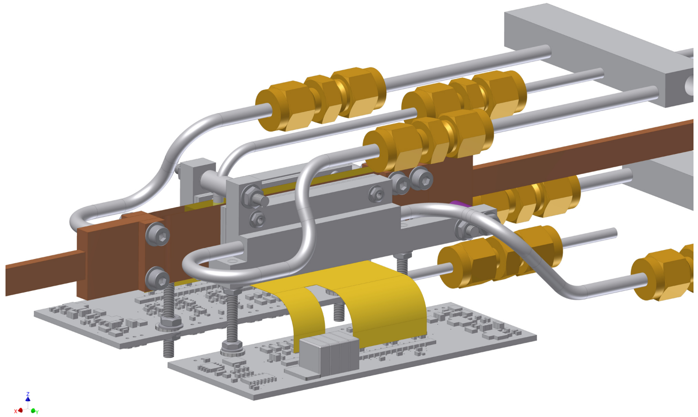


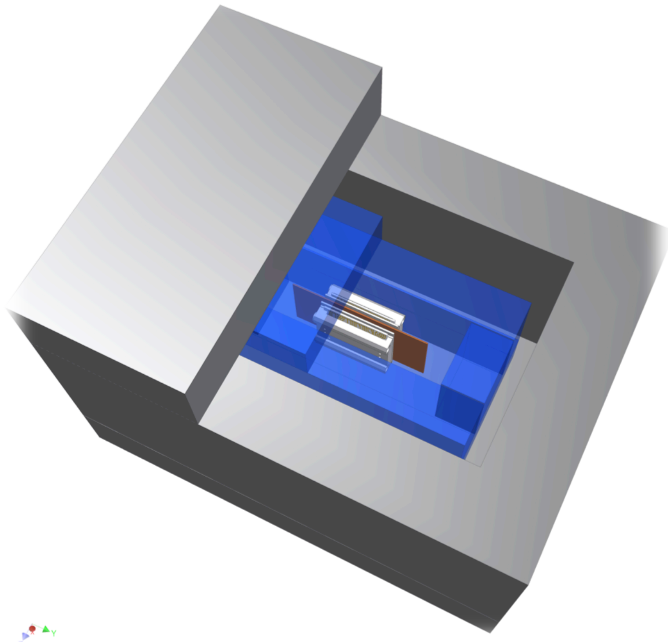




Sketch of the VIP2 Setup:
Cu foil, 2x3 SDD x-ray detectors



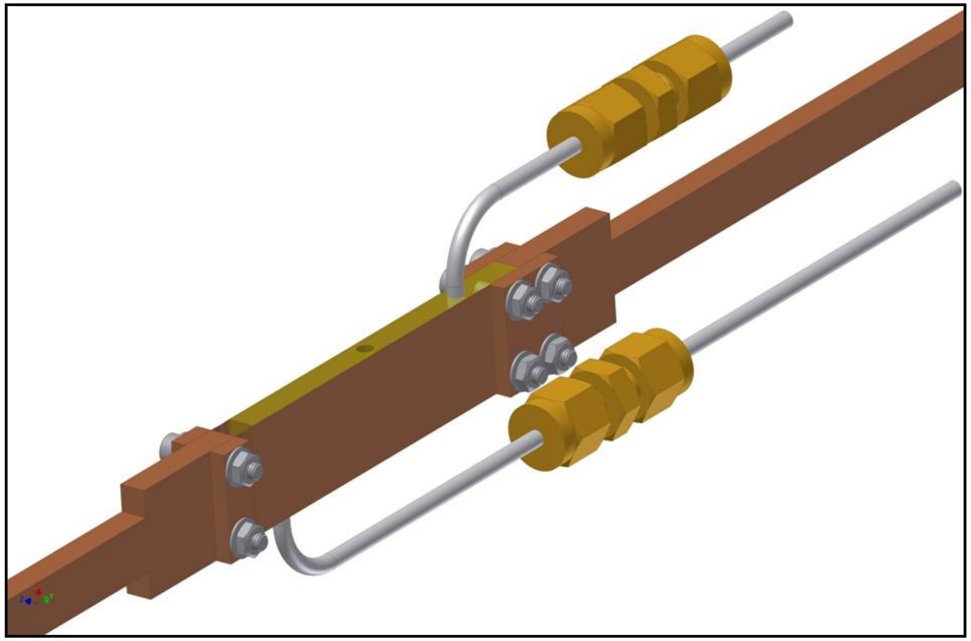


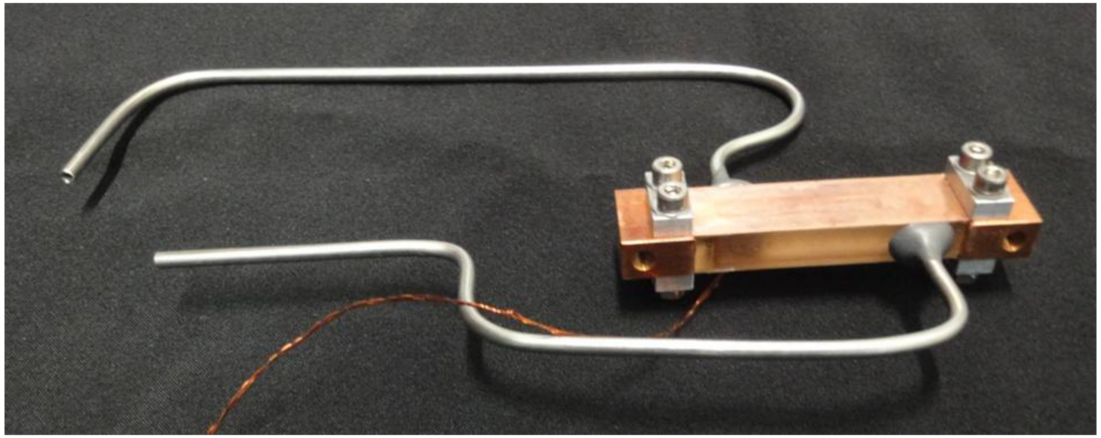


Copper target VIP2

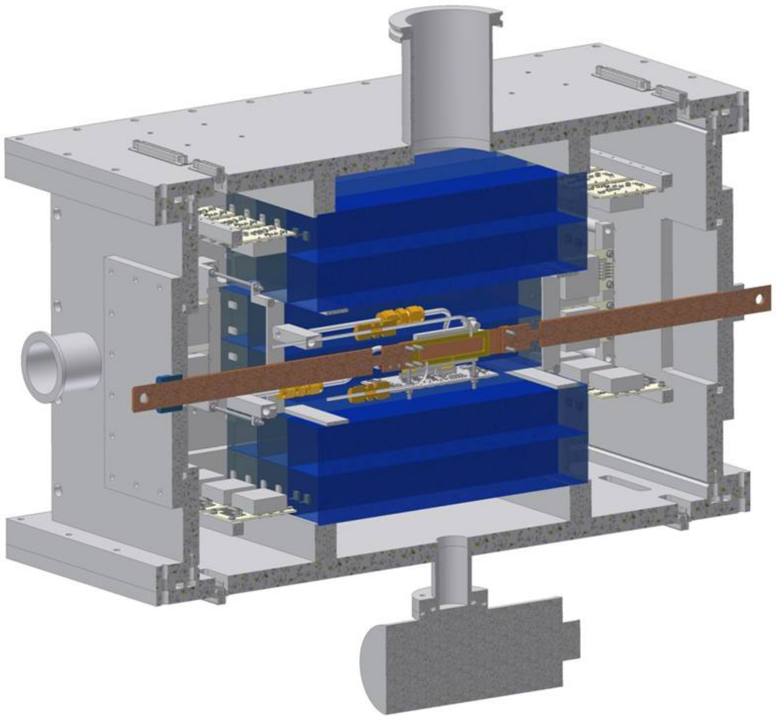
Length: 30 mm
Width: 10 mm
Cross section: 0.4 mm^2

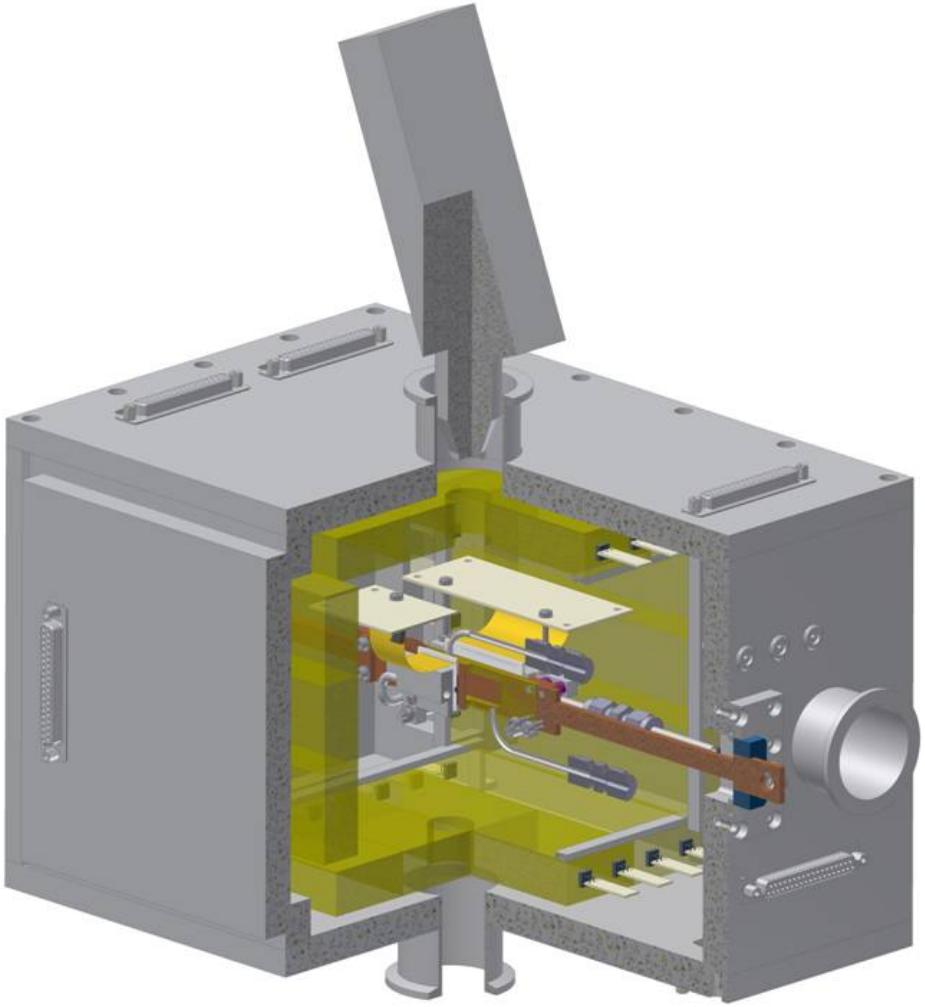
Current: 100 A



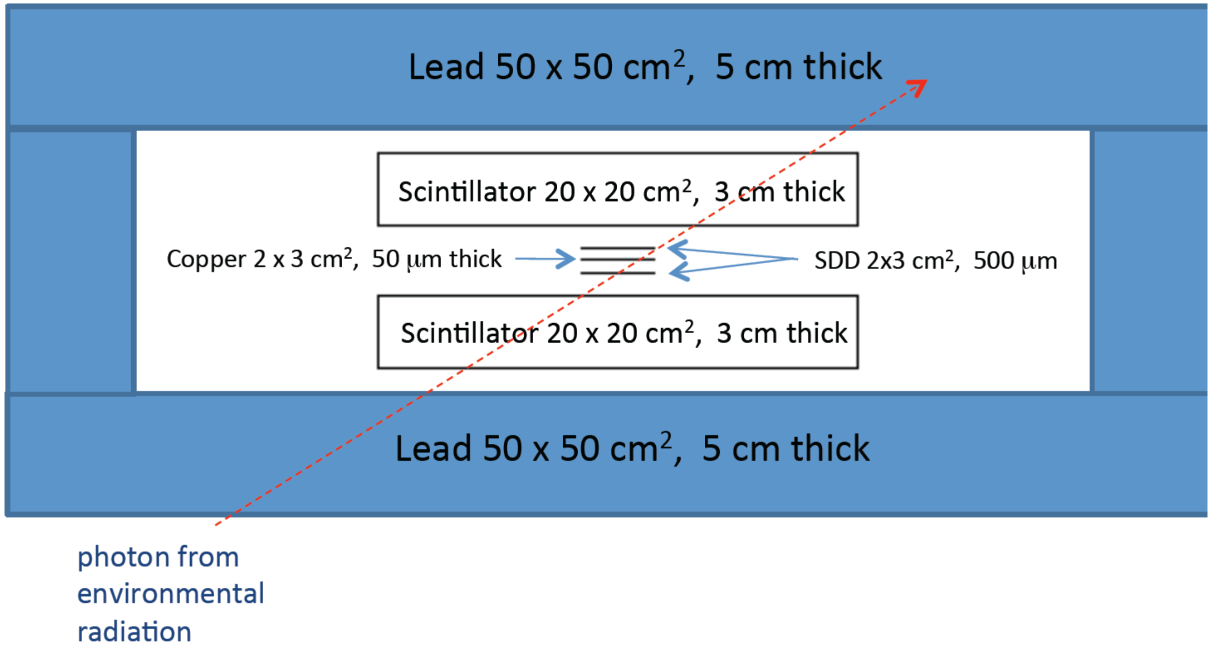


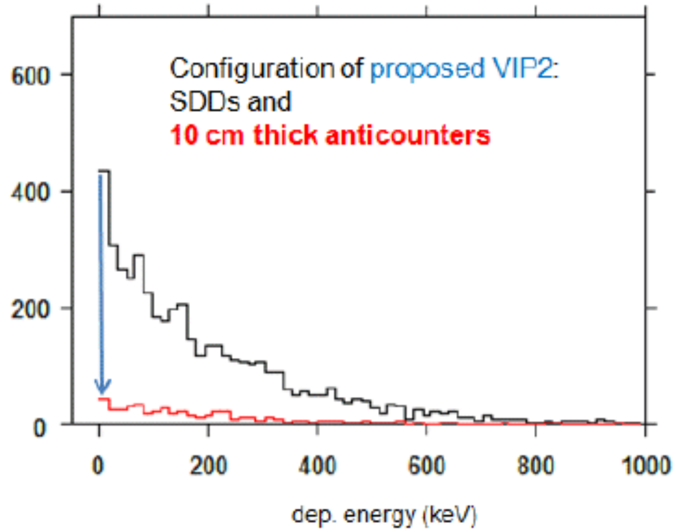
Sketch of the VIP2 Setup
Passive shielding removed





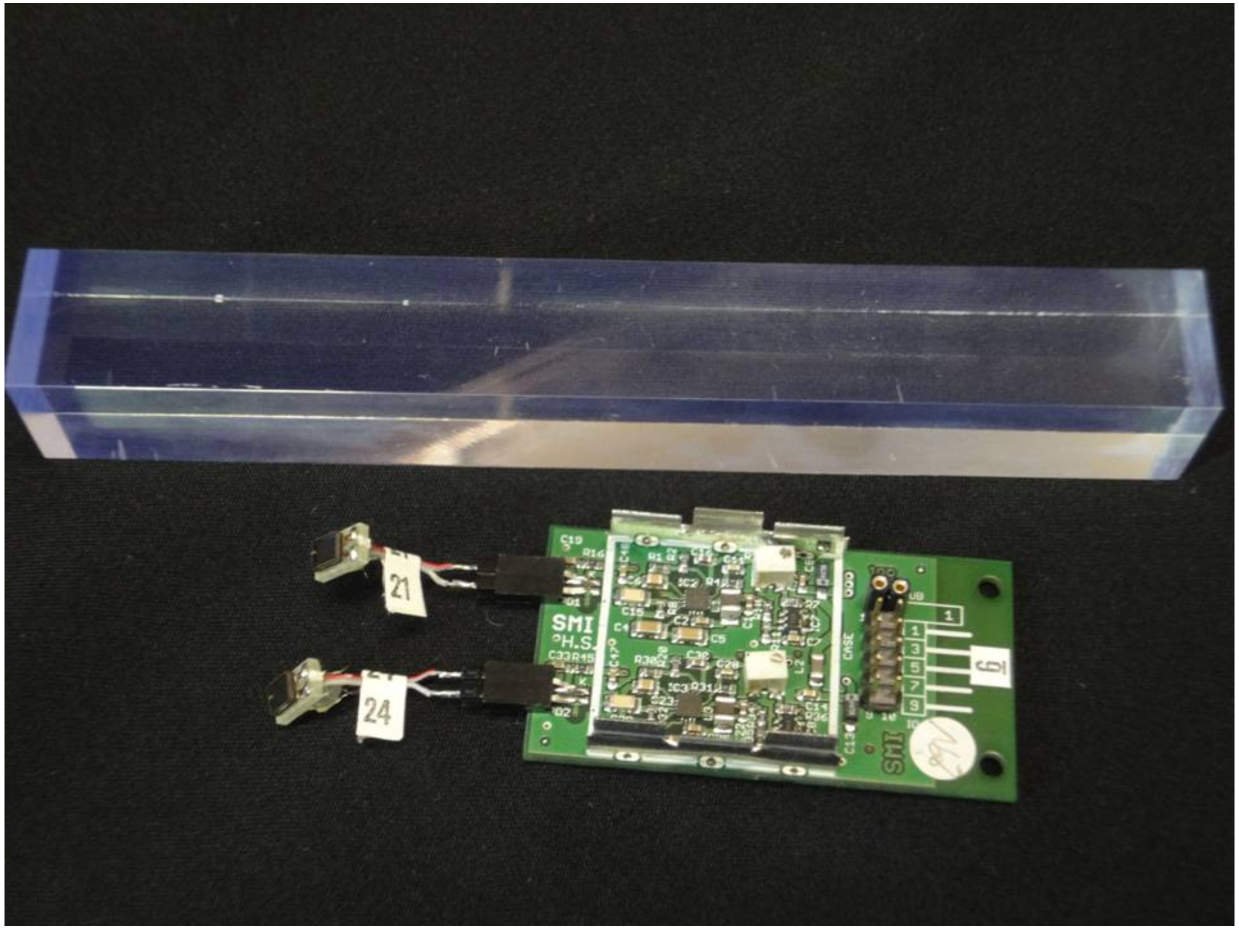
Background reduction for VIP2 by active shielding





Scheme of a setup with plastic scintillators sandwiching the SDD x-ray detectors (scheme for Monte-Carlo simulation)

VIP2 Active shielding with scintillators



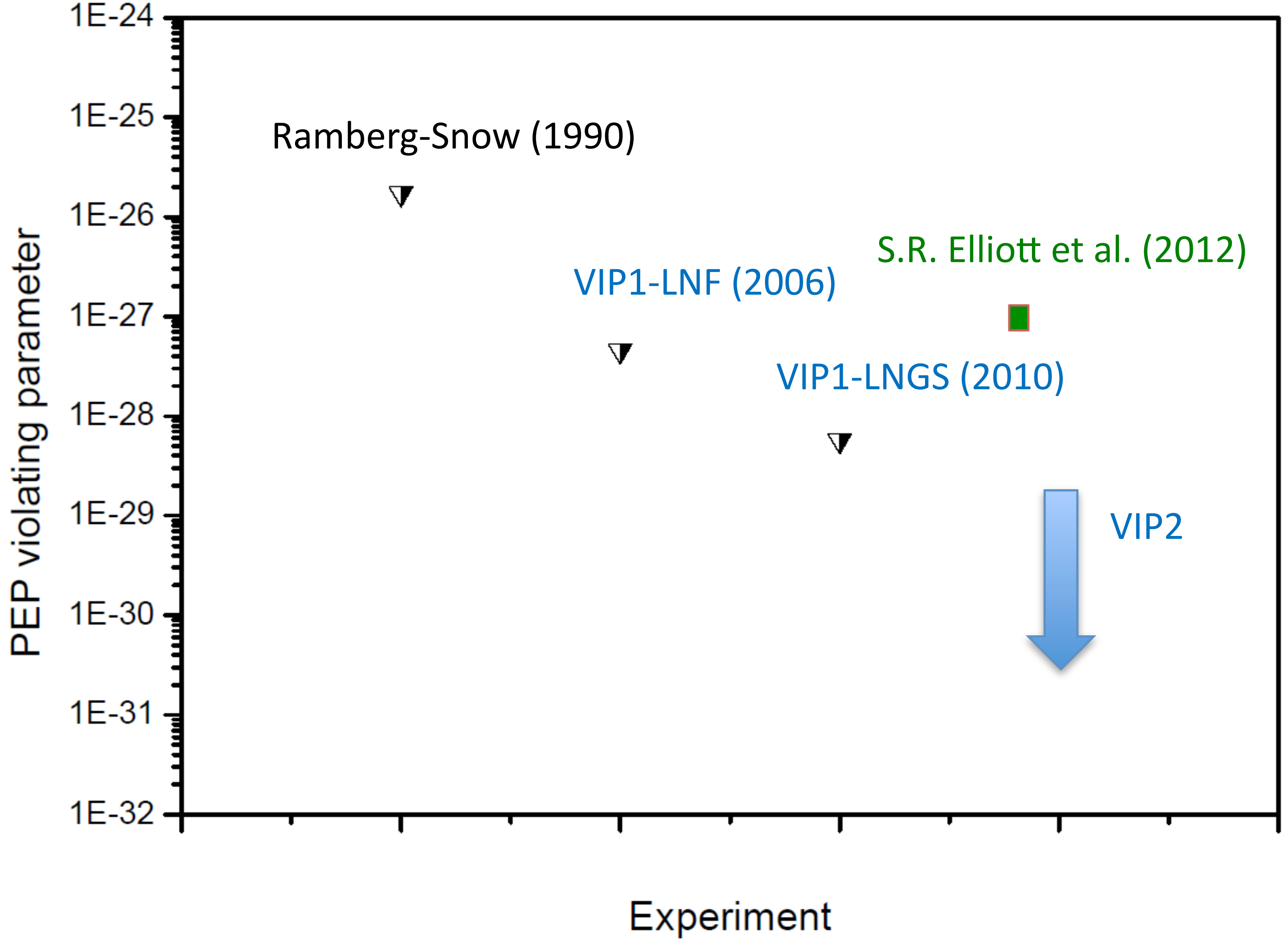
40x32x250 cm

Readout with SiPM

VIP2 Features

Changes		Factor
Acceptance	12% (1%)	12
Higher current	100A (50A)	2
Reduced length	3 cm (8.8 cm)	1/3
Total linear factor		8
Better SDD energy resolution	170 eV (340 eV)	4
Reduced active area	6 cm2 (114 cm^2)	20
Better shielding and veto		5-10
Higher SDD efficiency		1/2
Background reduction		200-400
Overall improvement		>120

→ Limit from 10^{-29} to 10^{-31}


1E-24
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1E-32
PEP violating parameter
Ramberg-Snow (1990)
VIP1-LNF (2006)
S.R. Elliott et al. (2012)
VIP1-LNGS (2010)
VIP2
Experiment

Summary and Outlook

- Pauli principle – a fundamental rule of nature but difficult to explain in a simple way.
- Pauli principle violation can be studied searching for Pauli-forbidden atomic transitions (using "new" electrons) with very high sensitivity.
- VIP experiment in Gran Sasso set the best limit ($\approx 10^{-29}$) for PEP violation for electrons using the Ramberg-Snow method.
- VIP aims at improving the sensitivity by orders of magnitudes (new X-ray detectors, active shielding).

In spite of the fact that at present we have no theoretical self-consistent framework for a description of violation of charge conservation and/or the exclusion principle, I do not think that experimentalists should stop testing these fundamental concepts of modern physics.

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

Thank you for your attention

Spare

Different interpretation

Alternative analysis S.R. Elliott, arxiv:1107.3118v2, January 2012)

Consider free electron collisions with atoms

$$\frac{\beta^2}{2} < \frac{\Delta N_X}{g_f} \frac{1}{P N_{new}^{free} N_{\mathrm{int}}^{free}}$$

$$N_{\mathrm{int}}^{free} = \Delta t \frac{v_f}{\mu}$$

$$N_{new}^{free} = N_e V$$

Experiment	N_e (/cm^3)	V (cm^3)	v_f (cm/s)	$N_{int}^{free} \times N_{new}^{free}$	$\frac{N_{3\sigma}}{\epsilon_{tot}}$	$\frac{1}{2}\beta^2$
VIP-UG	8.41×10^{22}	1.2	1.57×10^8	1.03×10^{44}	5×10^4	8.4×10^{-39}
This Work	1.33×10^{23}	36.1	1.83×10^8	6.88×10^{45}	1.64×10^5	2.6×10^{-39}