Testing spin statistics at Gran Sasso Underground laboratory

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INFN, Laboratori Nazionali di Frascati

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Pauli Exclusion Principle (PEP)

In its original form by Pauli:

> *"In an atom there cannot be two or more equivalent electrons for which the values of all four quantum numbers (*n, l, m_l, m_s*) coincide. If an electron exists in an atom for which all of these numbers have definite values, then this state is 'occupied'."*

Then extended to all fermions

Feynman Lectures on Physics:

"Why is it that particles with half-integral spin are Fermi particles (...) whereas particles with integral spin are Bose particles (...)?

We apologize for the fact that we can not give you an elementary explanation.
An explanation has been worked out by Pauli from complicated arguments from 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 to reproduce his arguments on an elementary level.

It appears to be one of the few places in physics where there is a rule which can be stated very simply, but for which no one has found a simple and easy explanation. (...)
This probably means that we do not have a complete understanding of the fundamental principle involved."

Pauli Exclusion Principle (PEP)

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

Proof of spin-statistics theorem by Lüders and Zumino

Postulates:

1 - The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)

2 - Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality – microcausality)

3 - The vacuum is the state of lowest energy

4 - The metric of the Hilbert space is positive definite

5 - The vacuum is not identically annihilated by a field

From these postulates it follows that (pseudo)scalar fields commute and spinor fields anticommute.

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

Pauli Exclusion Principle (PEP)

Theories of Statistics Violation

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

"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……"

Ignatiev & Kuzmin model: Fermi oscillator with a third state

(Ignatiev, A.Y., Kuzmin, V. , Quarks '86: Proceedings of the 229 Seminar, Tbilisi, USSR, 15-17 April 1986)

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

***β* quantifies the degree of violation in the transition** $|1\rangle \rightarrow |2\rangle$

Govorkov, A. can not be genelized to quantum field theory! Physics Letters A 1989, 236 137, 7–10.

Pauli Exclusion Principle (PEP)

- Greenberg, O.W.; Mohapatra, R.N.

Local Quantum Field Theory of Possible Violation of the Pauli Principle.
q parameter deforms anticommutators $a_k a_l^+ - q a_l^+ a_k = \delta_{k,l}$

Physical Review Letters 1987, 59, 2507

Govorkov, A. non relativistic! Physica A: Statistical Mechanics and its Applications 1994, 203, 655

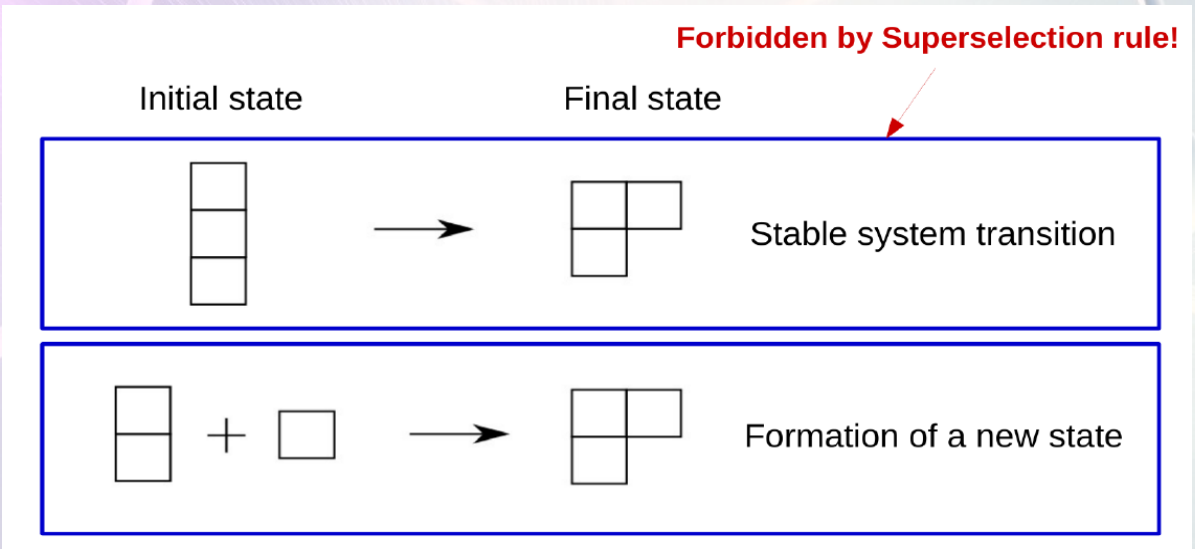
- In the absence of a complete relativistic theory alternative compatible with Quantum Mechanics → Rahal, V.; Campa, A. , Physical Review A (1988) 38, 3728

  the global w. f. describing the totality of the electrons is not exactly antisymmetric → PEP mostly holds as long as the number of wrongly entangled pairs is small.

  The non-Paulian character is intrinsic of the global w. f. → can be tested looking for signature of a violating interaction of a wrongly entangled pair.

Messiah – Greenberg superselection rule

Superpositions of states with different symmetry are not allowed →
transition probability between two symmetry states is ZERO

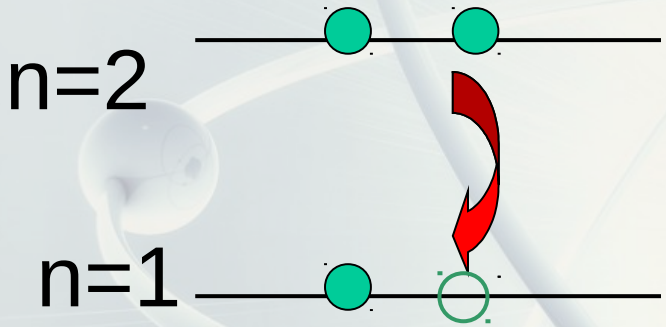


Process	MG conform	Limit for PEP violation	Experiment
anomalous atomic transition	Yes	4.7×10^{-29}	VIP [4]
anomalous atomic transition	No	1.3×10^{-47}	DAMA/LIBRA [5]
anomalous nuclear transition	No	2.2×10^{-57}	Borexino [6]

The VIP experiment sets lowest limit in an experiment in accordance with the MG superselection rule.

Experimental method:

Search for anomalous X-ray transitions when bringing “new” electrons



Normal 2p → 1s transition

Energy 8.04 keV

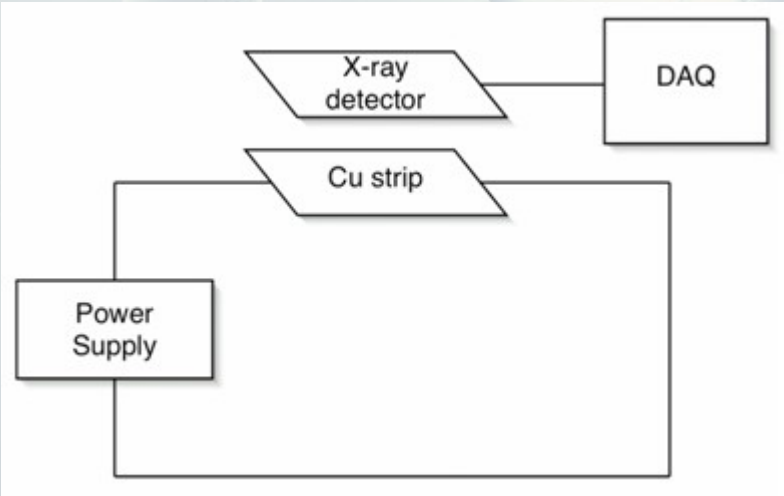
2p → 1s transition violating Pauli principle

Energy 7.7 keV

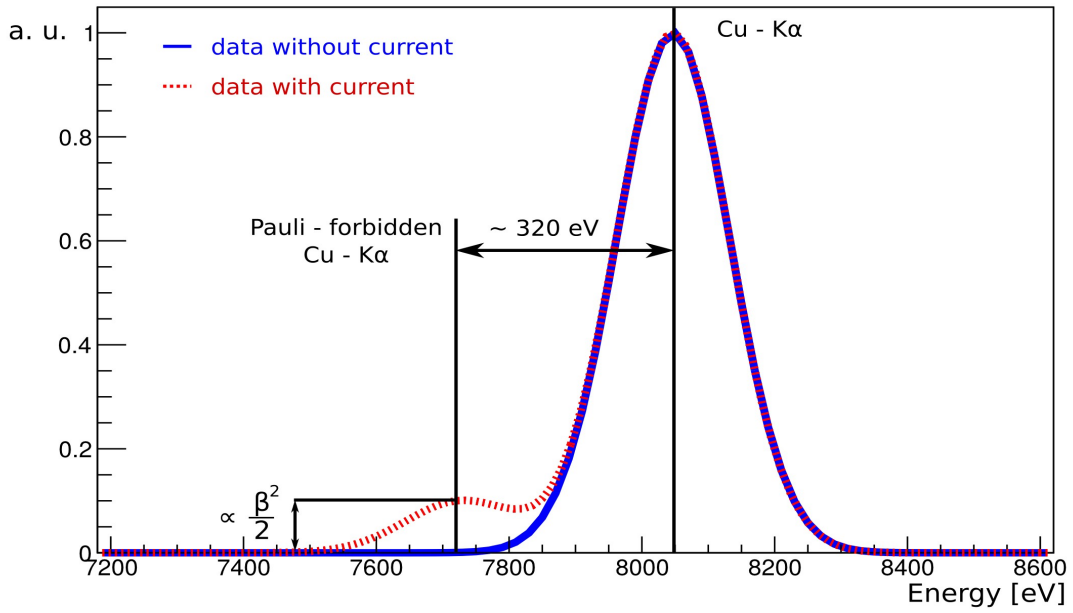
Pre-VIP : Ramberg and Snow (RS)

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

Search for anomalous electronic transitions in Cu induced by a circulating current ("new" external electrons, which interact with the valence electrons), namely transition from 2p to 1s already filled by 2 electrons, alternated to X-ray background measurements without current



Undesired result :



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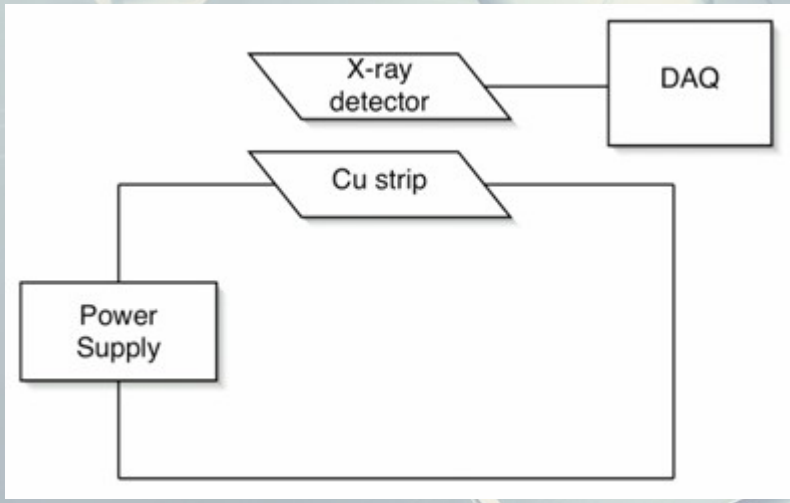


$$N_X \geq \beta^2 \left(0.90 \cdot 10^{28}\right)$$

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

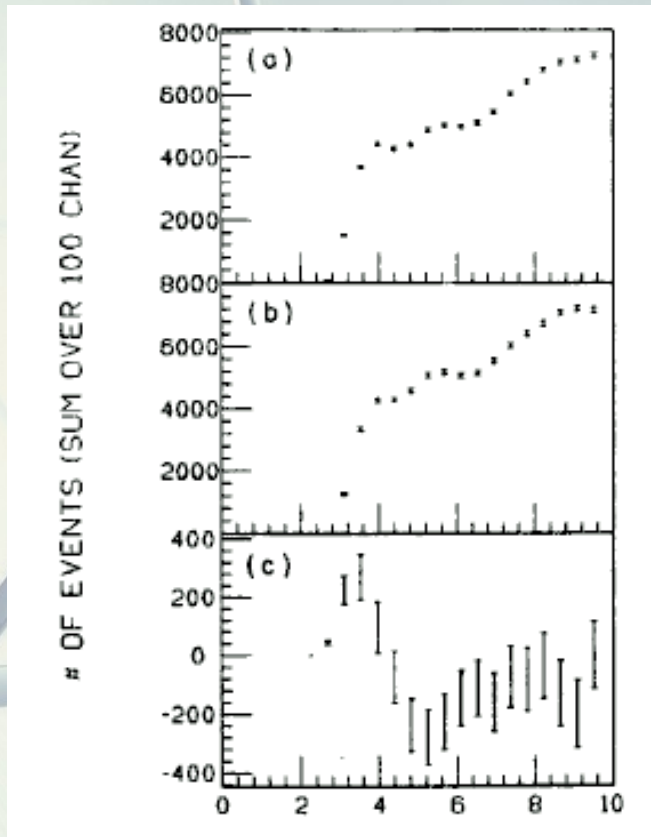
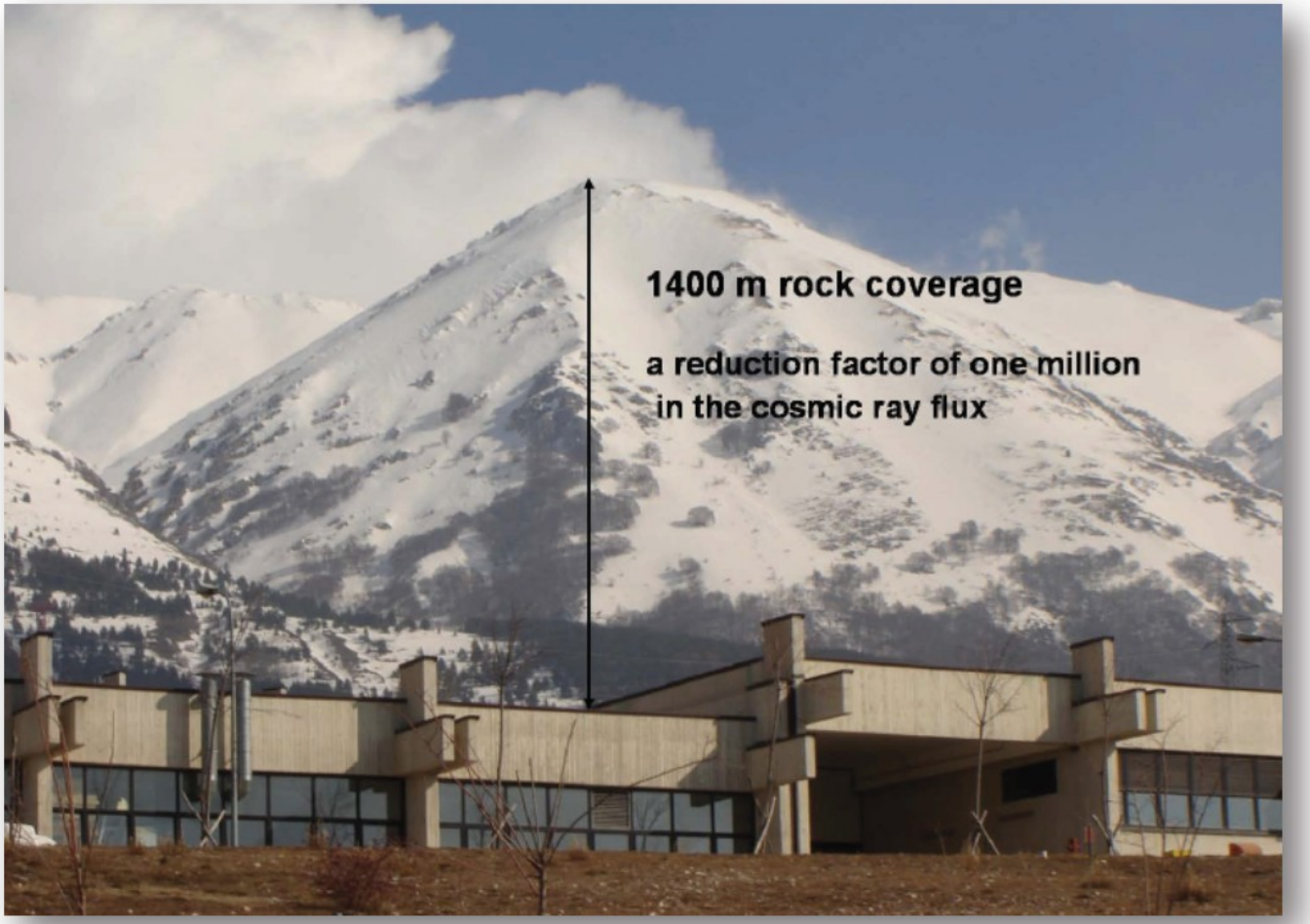


Fig. 2. (a) Number of triggers summed over 100 ADC channels, plotted versus equivalent X-ray energy with current-on in copper strip below X-ray counter. (Note the points are separated by 50 channels, so that only every other point is statistically independent). (b) Same as (a) but with no current passing through an identical strip of copper. (c) Difference between (a) and (b) after normalization at the 9.5 keV point.

VIP Experiment & LNGS



VIP Experiment & LNGS

Goal: improve the R&S PEP violation limit ($\beta^2/2 < 1.7 \times 10^{-26}$) by 3-4 orders of magnitude!

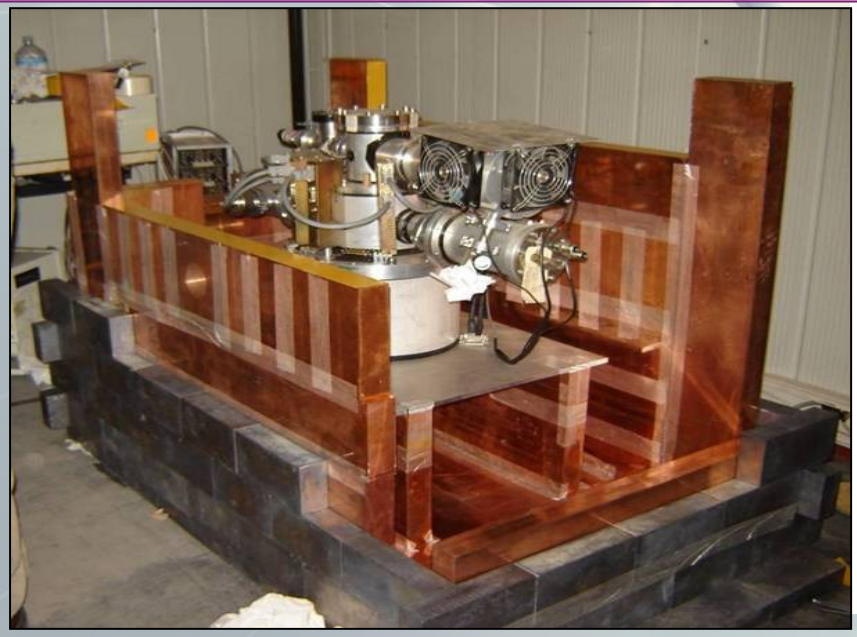
VIP setup: a) copper ultrapure cylindrical foil b) surrounded by 16 Charge Coupled Devices (CCD)

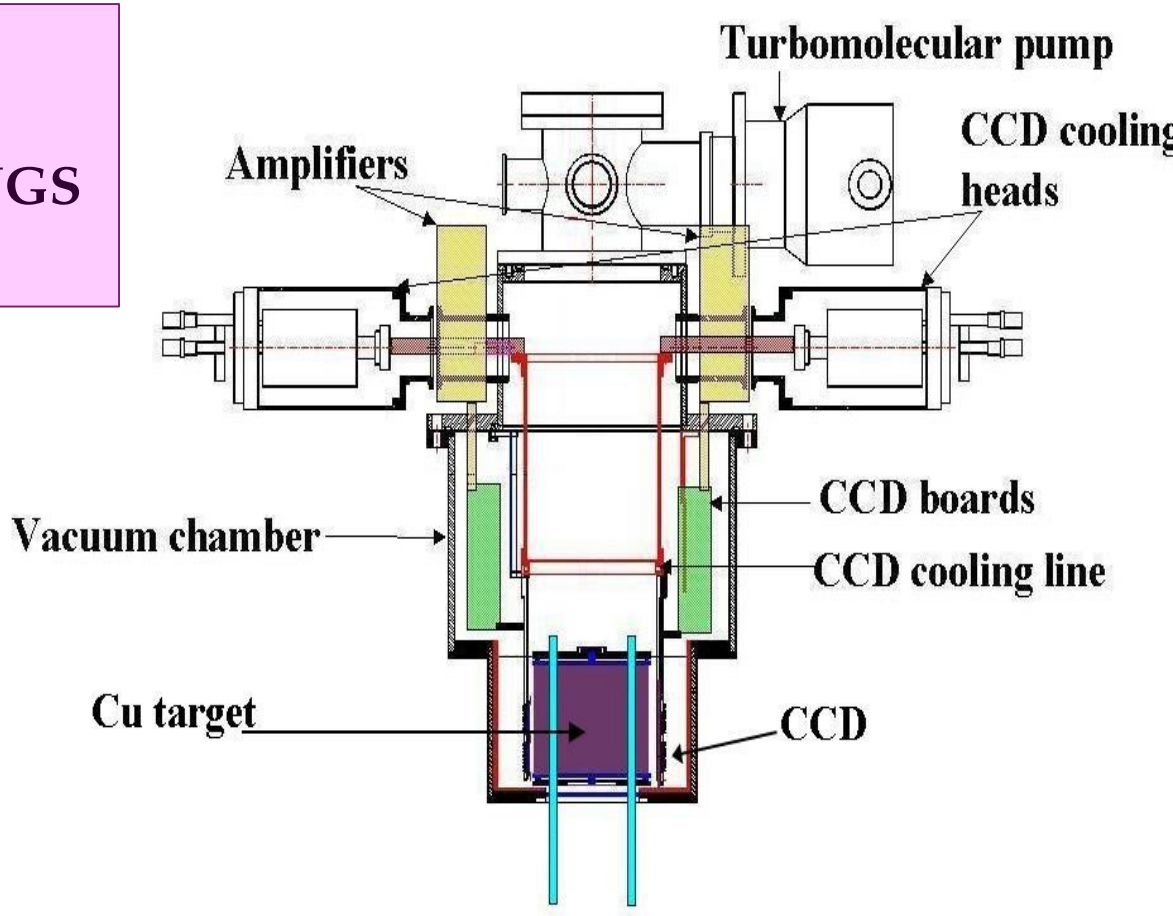
c) inside a vacuum chamber: CCDs cooled to 168K by a cryogenic system

d) amplifiers + read out ADC boards.

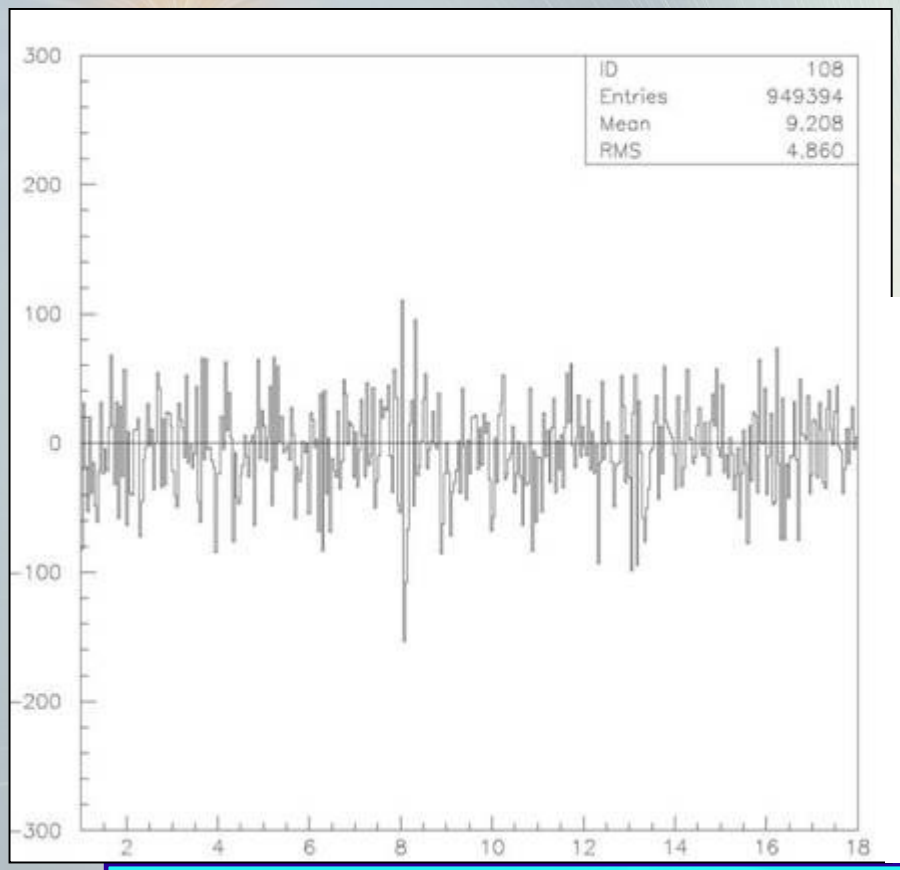
Advantages

- **High resolution CCDs**
- **Low background environment LNGS**
- **High statistics.**





VIP Experiment



PEP violation Probability:

After about 2 years running

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

(Preliminary)

We have thus improved the limit obtained by Ramberg & Snow by a factor 400

(Foundation of Physics 41 (2011) 282+ other papers)

VIP-2 goal 2 OM improvement

a) Silicon Drift Detectors (SDDs) → higher resolution, faster (triggerable) detectors

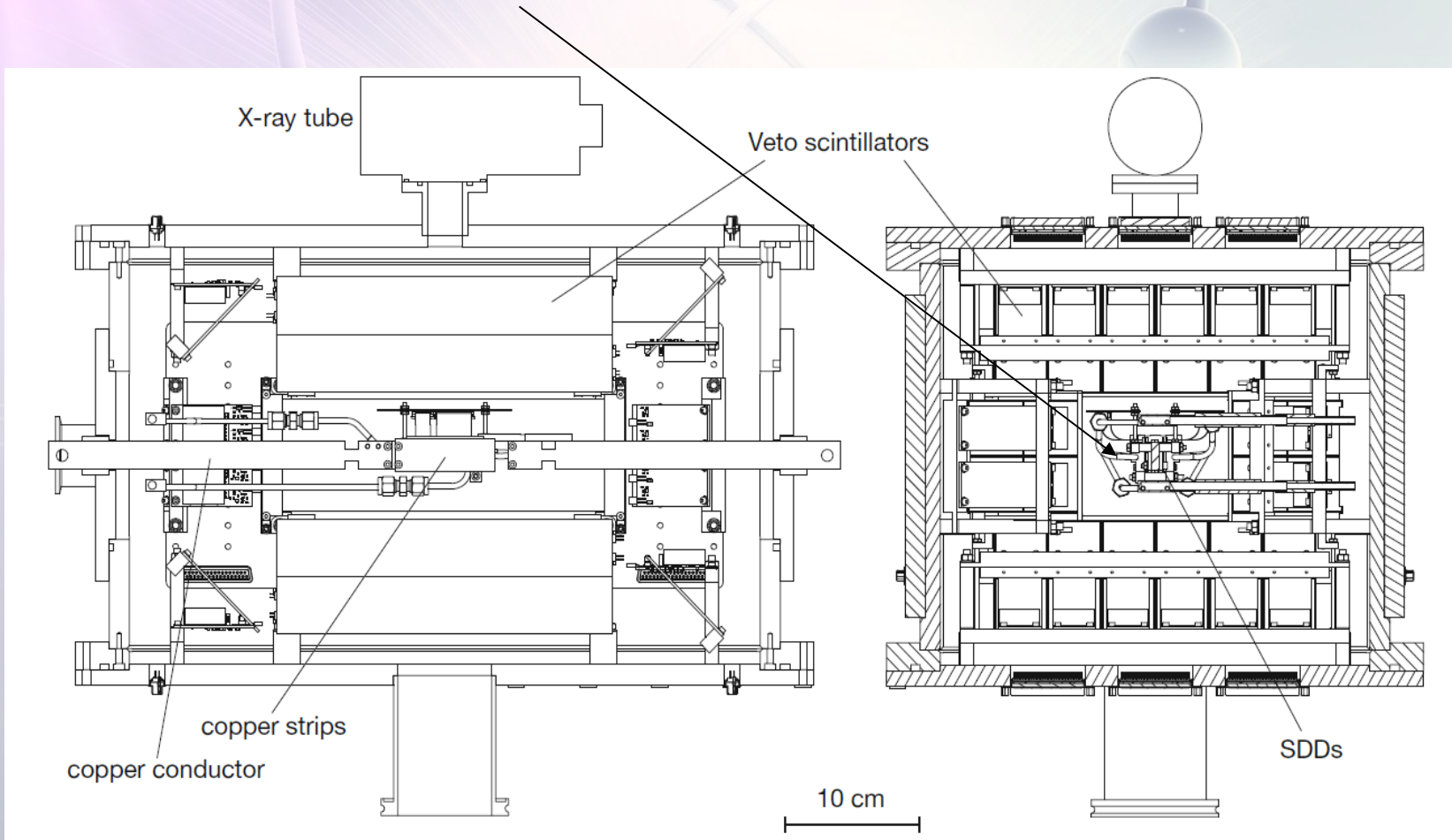
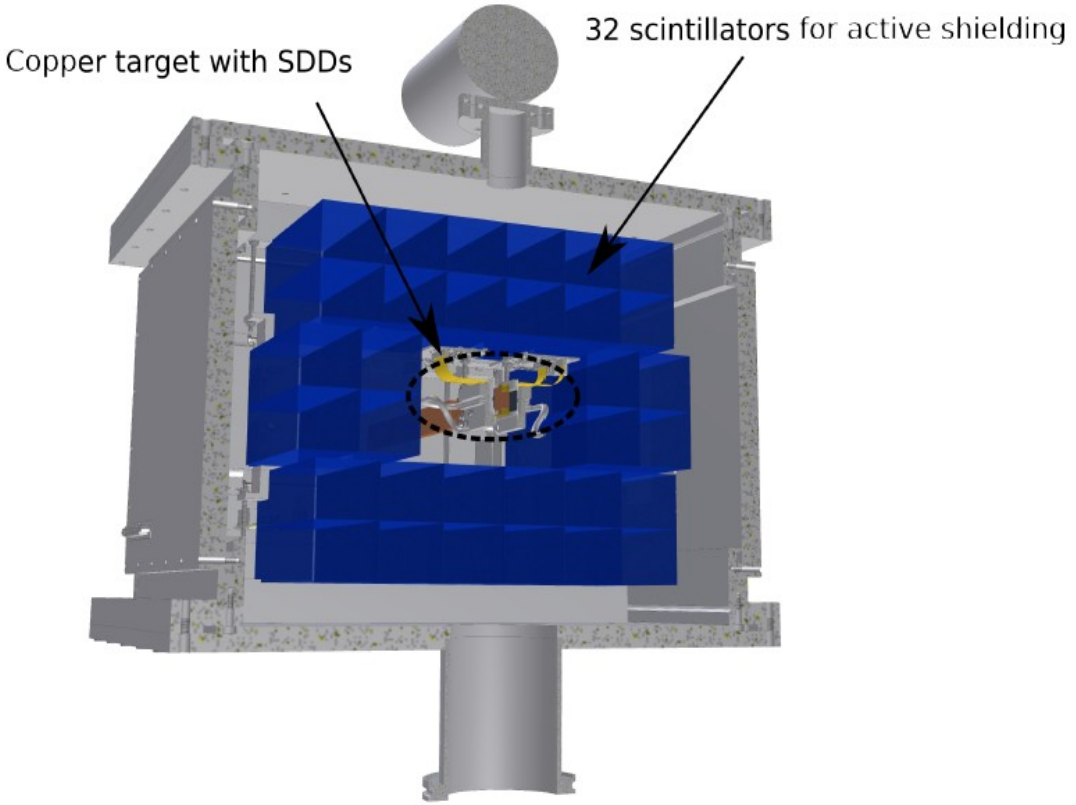


Fig. 1 The side views of the design of the core components of the VIP-2 setup, including the SDDs as the X-ray detector, the scintillators as active shielding with silicon photomultiplier readout

VIP-2 goal 2 OM improvement

b) VETO system (32 plastic scintillators + SiPMs read out) → rejection of background (high energy charged particles) from outside the detector



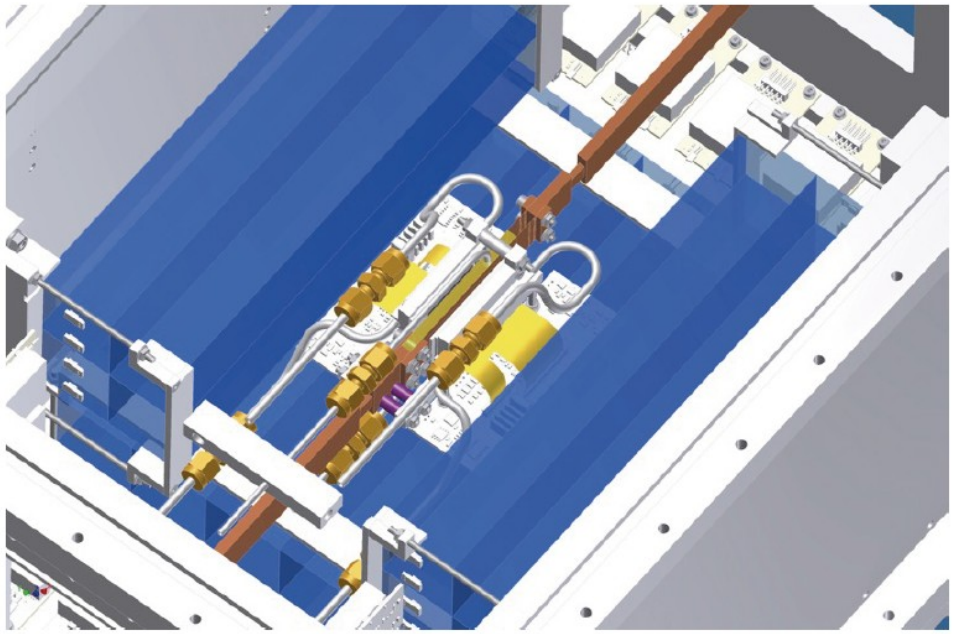
32 scintillators (blue) read out by two Silicon Photomultipliers each, are installed around the SDDs to give an active veto signal.

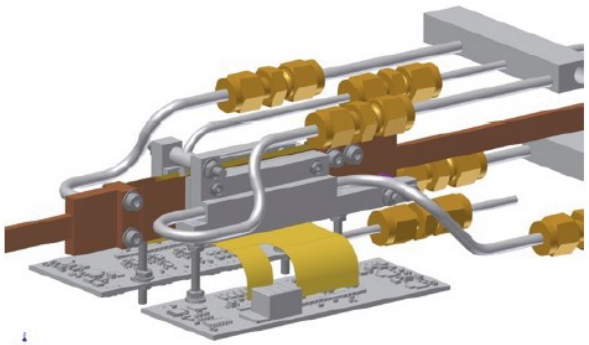
VIP-2 goal 2 OM improvement

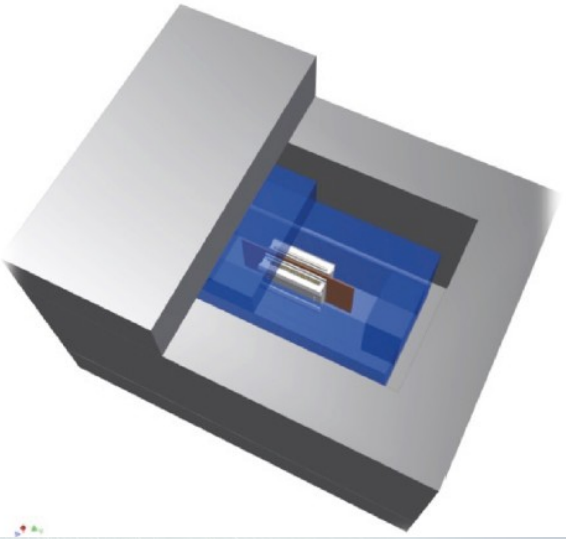
c) more compact target → higher acceptance

d) Cu strips cooled by a closed Fryka chiller circuit → higher current (100 A) @ 20 °C of Cu target implies 1 °K heating in SDDs

Sketch of the VIP2 Setup:







VIP-2 goal 2 OM improvement

e) quick (one hour) resolution and energy calibration. X-ray tube irradiates zirconium & titanium

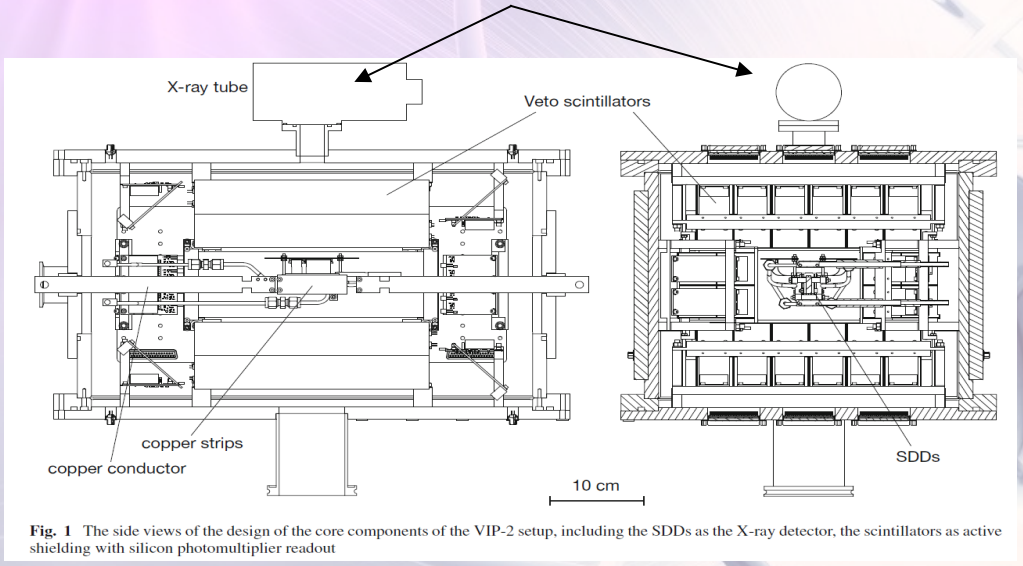
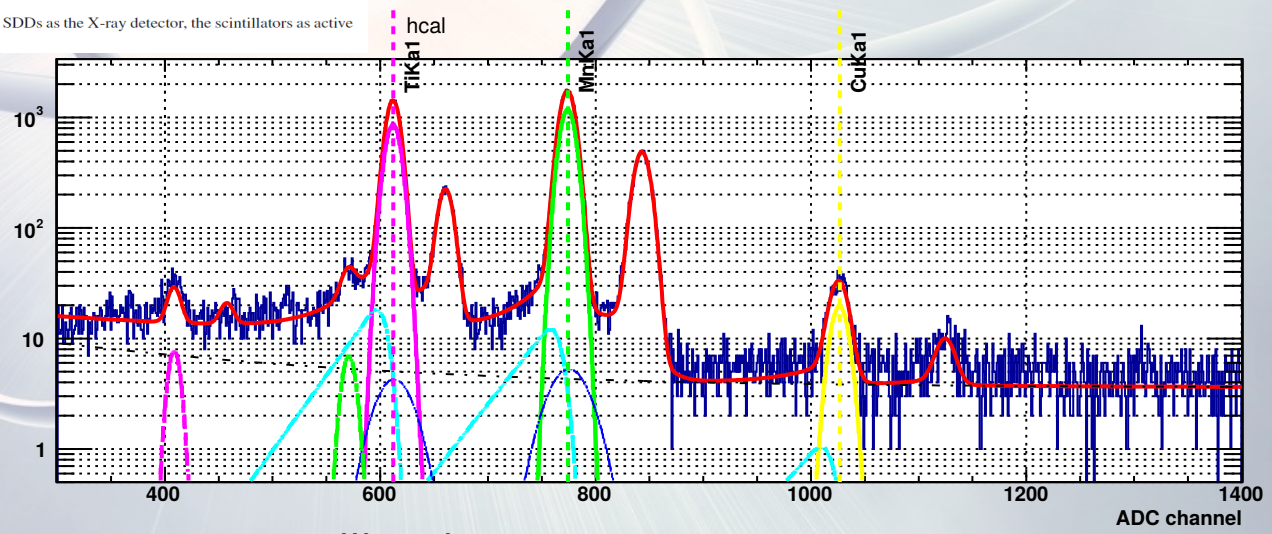


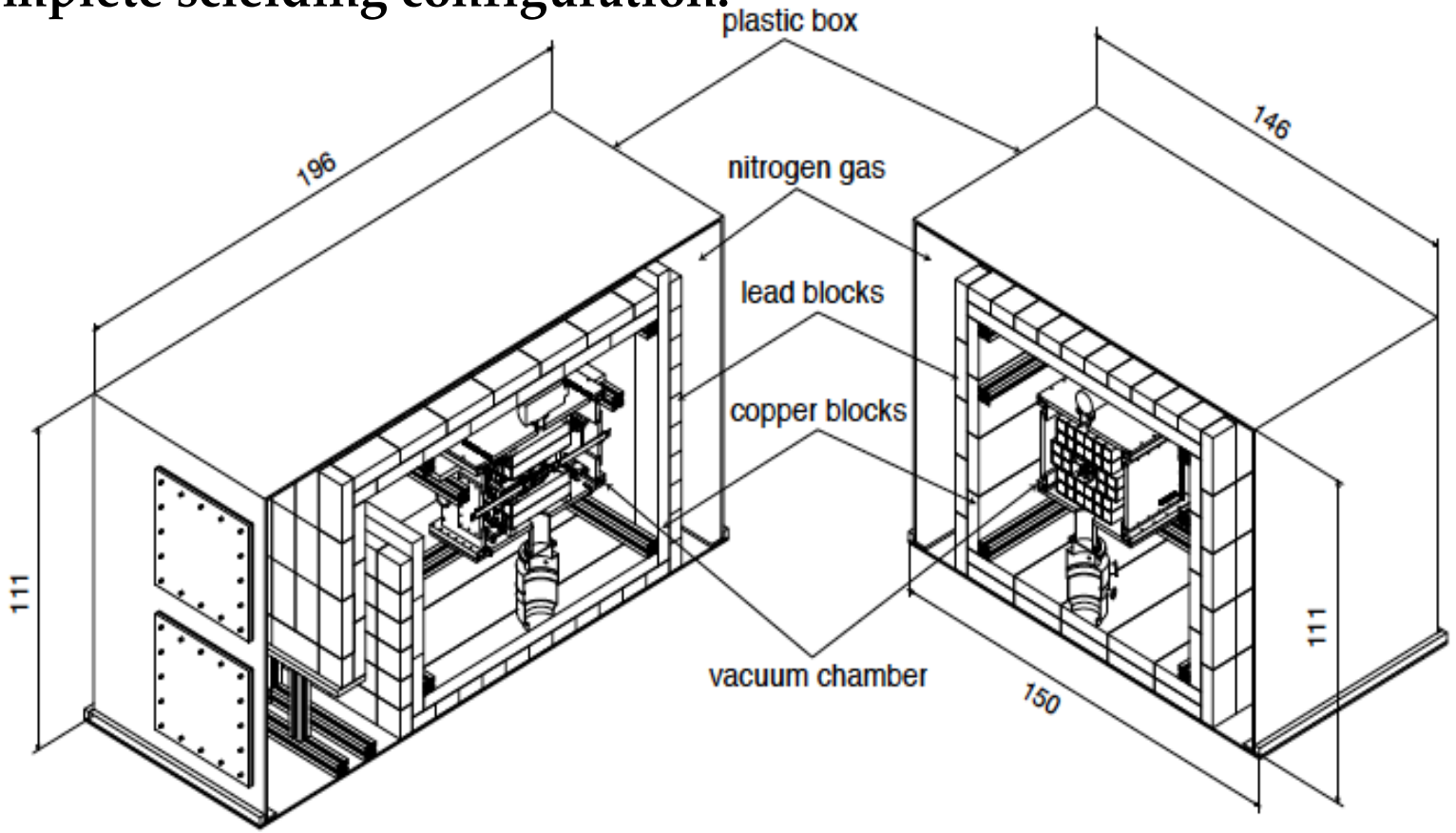
Fig. 1 The side views of the design of the core components of the VIP-2 setup, including the SDDs as the X-ray detector, the scintillators as active shielding with silicon photomultiplier readout



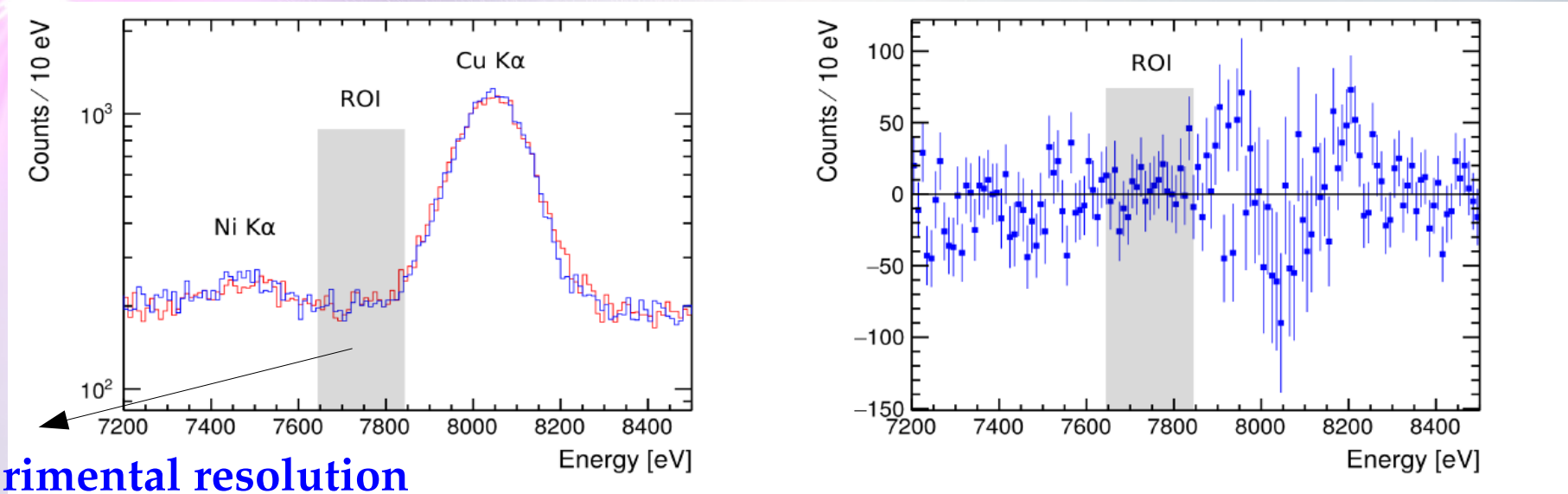
- SDD calibration spectrum at 125 K
- Energy resolution 150 eV (FWHM) for Mn Kα

VIP-2 goal 2 OM improvement

Complete scielding configuration:



pre-VIP-2 (w.o. shielding) results



experimental resolution

The data measured at LNGS with current (red) and without current (blue) on the left side. The subtracted spectrum is shown on the right. No excess of events is found in the region of interest (ROI - grey) of the searched PEP violating.

3s of the subtracted number of counts in the ROI

$$\Delta N_x \geq \frac{\beta^2}{2}\frac{1}{10}\frac{D\sum(I\Delta t)}{\mu e}(\text{detection efficiency})$$

$$\frac{\beta^2}{2} \leq \frac{10\mu e}{D\sum(I\Delta t)}\frac{\Delta N_x}{(\text{detection efficiency})}$$

mean free path μ	target length D	current I	data taking time Δt	detection efficiency
3.91×10^{-6} cm	7.1 cm	100 A	81 days 10 hours	1.82 %

$$\frac{\beta^2}{2} \leq \frac{3 \times 91}{1.46 \times 10^{31}} = 1.87 \times 10^{-29}$$

factor 2.5 gain respect to VIP

pre-VIP-2 (w.o. shielding) results

Same data set - simultaneous fit of the "sig + bkg" and bkg spectra, in order to use all the information available for the background shape from the data. The obtained fits:

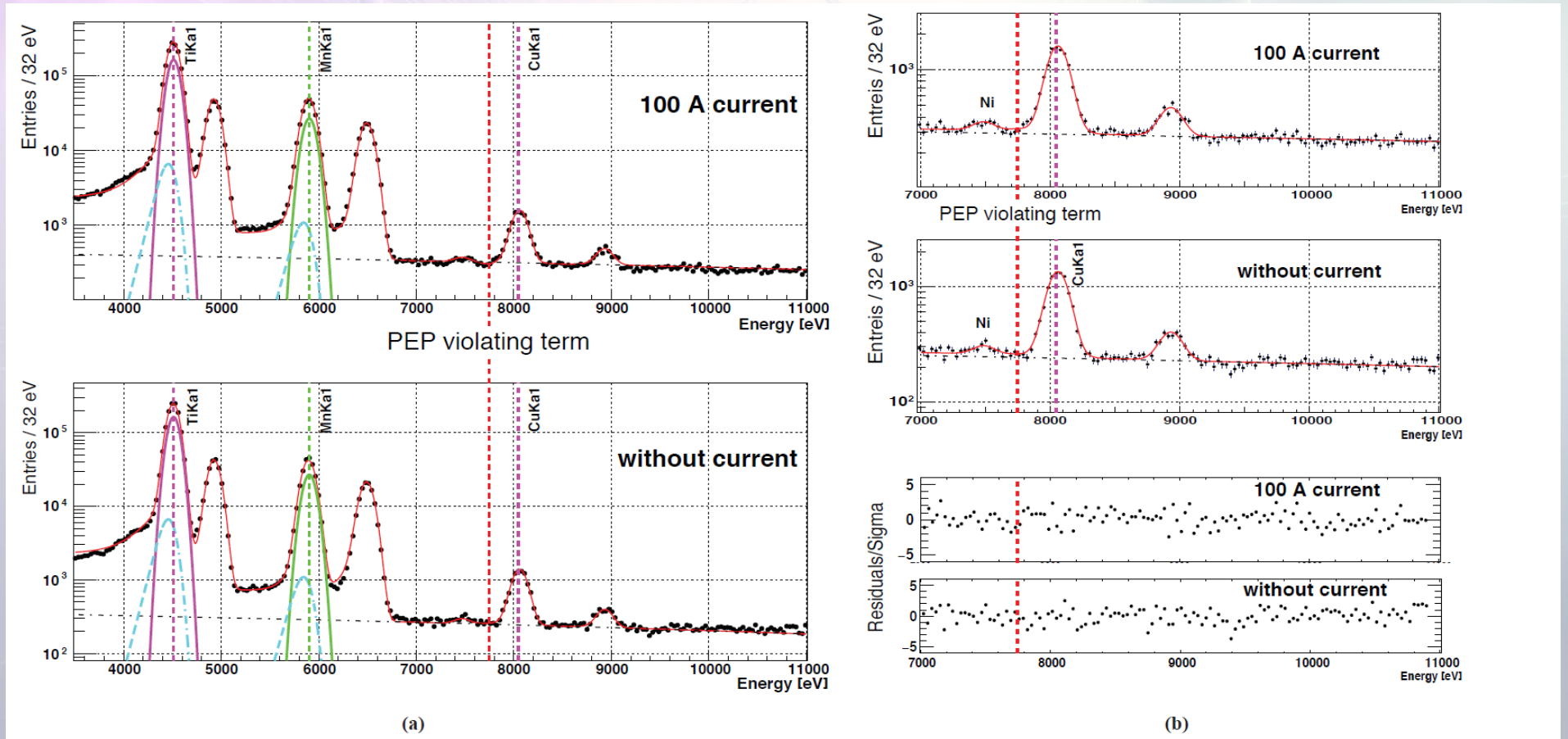


Fig. 8 A global chi-square function was used to fit simultaneously the spectra with and without 100 A current applied to the copper conductor. The energy position for the expected PEP violating events is about 300 eV below the normal copper $K_{\alpha 1}$ transition. The Gaussian function and the tail part of the $K_{\alpha 1}$ components and the continuous background from the fit result are also plotted. (a) : the fit to the wide energy range from 3.5 keV to 11 keV; (b) : the fit and its residual for the 7 keV to 11 keV range where there is no background coming from the calibration source.

pre-VIP-2 (w.o. shielding) results

Detalis of the analysis can be found in :

Eur. Phys. J. C (2018) 78:319
https://doi.org/10.1140/epjc/s10052-018-5802-4

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Experimental Physics

Experimental search for the violation of Pauli exclusion principle

VIP-2 Collaboration

Present limit with all the pre-VIP2 collected satatistiscs :

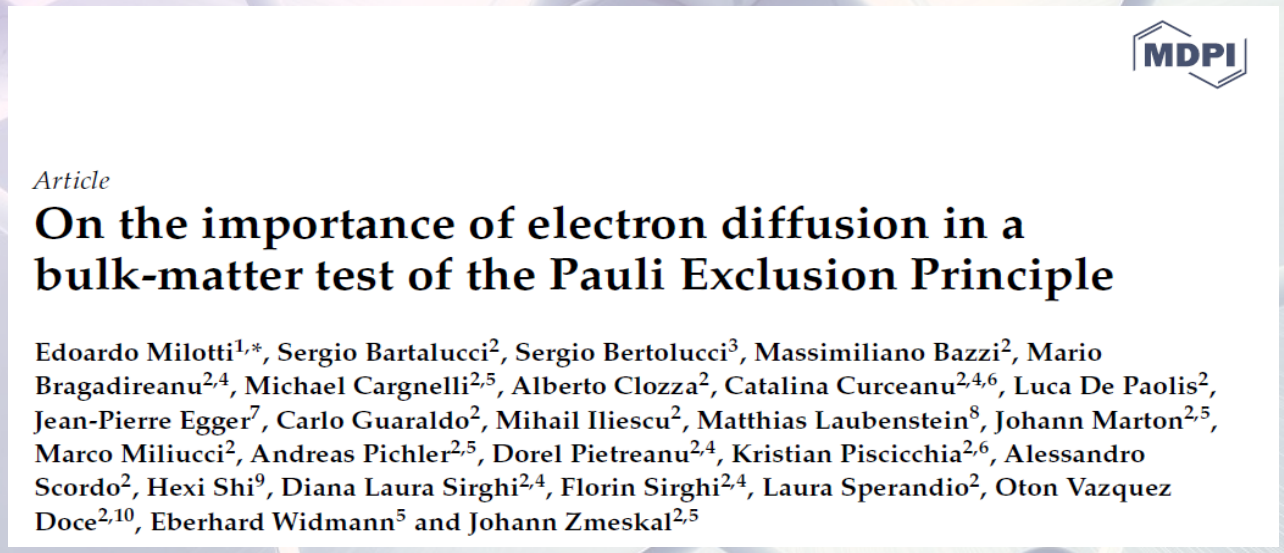
$$\frac{\beta^2}{2} \leq \frac{3 \times 82}{1.46 \times 10^{31}} = 1.69 \times 10^{-29}$$

Paper in preparation

pre-VIP-2 (w.o. shielding) results

Deeper investigation of the electrons diffusion and interaction in a bulk-matter:

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:



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 Vazquez Doce[2,10], Eberhard Widmann[5] and Johann Zmeskal[2,5]

The random walks of the electrons as they move from the entrance to the exit of the copper sample is fully described in terms of a diffusion transport model.

PEP violation studies with Pb target & Ge detector

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

relax the definition of *new* (fermion – fermion system interaction) giving rise to violating Ψ_{sym} .

Exploit free electrons in a conductor (Pb is ideal) → specific electron – specific atom interactions are so rare ~ 10^4 ys each interaction is a new PEP test

$$\frac{1}{2}\beta^2 < \frac{N_{3\sigma}}{\epsilon_{tot}} \frac{1}{P_{cpt} N_{new}^{free} N_{int}^{free}}$$

where N_{int}^{free} and N_{new}^{free} are given by

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

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

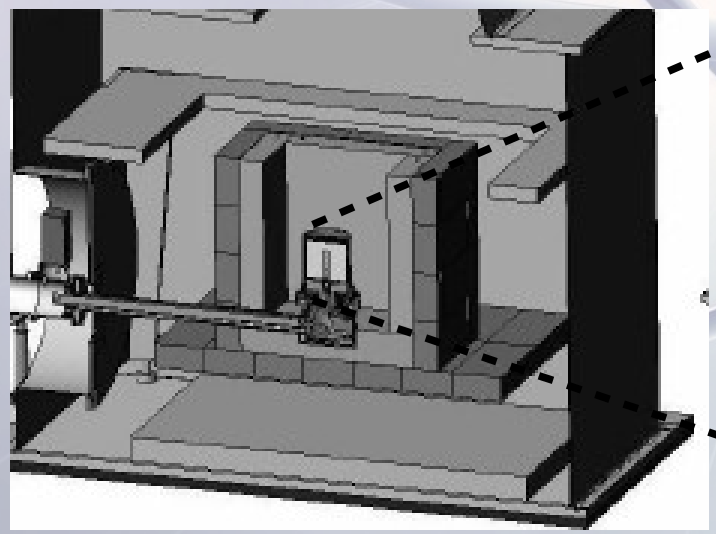
VIP lead with HPGe & LNGS

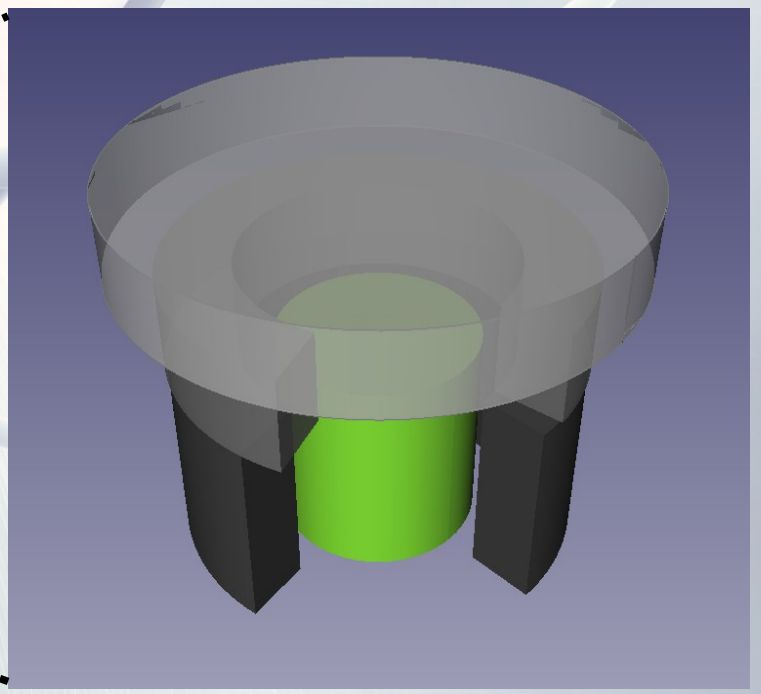
High purity Ge detector measurement:

- Ge detector surrounded by roman lead target + complex electrolytic Cu + Pb shielding

- 10B-polyethylene plates reduce the neutron flux towards the detector

- shield + cryostat enclosed in air tight steel housing flushed with nitrogen to avoid contact with external air (and thus radon).





VIP lead with HPGe & LNGS

What does rare interactions mean? How many "violating electrons" in the roman lead block could already do violating transitions?

$$P(k) = \frac{(T/N\tau)^k}{k!}\exp(-T/N\tau), \quad \longrightarrow \quad p = P(0) = \exp(-T/N\tau),$$

$$\begin{aligned} p &= \exp(-T/N\tau) + (1-P_{\rm cpt})\,\frac{(T/N\tau)}{1!}\exp(-T/N\tau) + \cdots + (1-P_{\rm cpt})^k\,\frac{(T/N\tau)^k}{k!}\exp(-T/N\tau) + \ldots \\ &= \sum_{k=0}^{k=\infty}(1-P_{\rm cpt})^k\,\frac{(-T/N\tau)^k}{k!}\exp(-T/N\tau) \\ &= \exp\left[-T/(N\tau/P_{\rm cpt})\right], \end{aligned}$$

so the PEP violation probability is to be corrected accordingly:

$$\frac{\beta^2}{2}\exp(-T_i P_{\rm cpt}/N\tau) < \frac{N_X}{\epsilon_{\rm tot} P_{\rm cpt} N_{\rm free} N_{\rm int}}$$

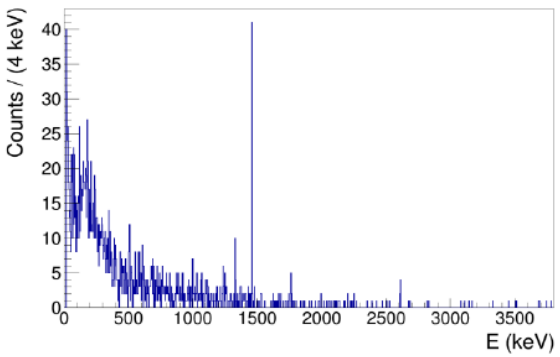
considering our 119 moles of roman Pb samples:

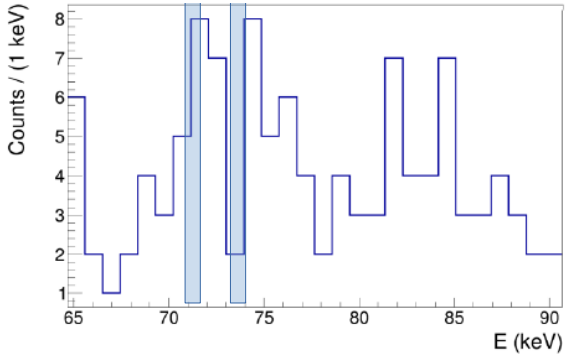
$$\exp(-T_i P_{\rm cpt}/N\tau) \approx 1.$$

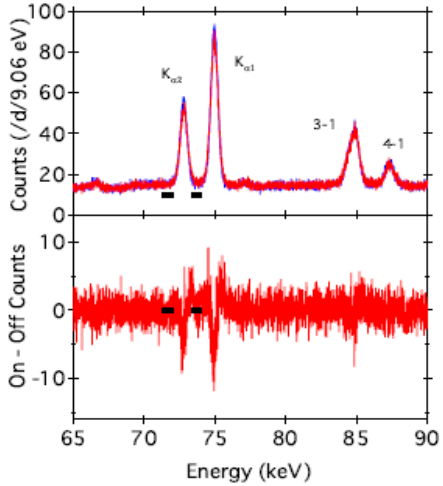
VIP lead with HPGe & LNGS

Extremely low statistics in the two ROI regions compatible with the mean bkg: b = 4.4 counts/keV

Transitions in Pb	forb.	allow.
1s - $2p_{3/2}$ $K_{\alpha 1}$	73713	74961
1s - $2p_{1/2}$ $K_{\alpha 2}$	71652	72798







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

Figure 1. Total measured X-ray spectrum (left); same spectrum in the region of the K_α standard and violating transitions in Pb (right).

The p value (probability of having measured an excess with respect to b in the two ROIs):

$$p = \sum_{j=z_1+1}^{\infty} \frac{b^{z_1}}{z_1!}\exp(-b) \sum_{j=z_2+1}^{\infty} \frac{b^{z_2}}{z_2!}\exp(-b) = \left[1 - \sum_{j=0}^{z_1} \frac{b^{z_1}}{z_1!}\exp(-b)\right]\left[1 - \sum_{j=0}^{z_2} \frac{b^{z_2}}{z_2!}\exp(-b)\right]$$

p = 0.051 corresponding to 1.95 standard deviations.

$$\frac{1}{2}\beta^2 < 1.58 \cdot 10^{-40}$$

Factor 16 better then Elliott

Paper in preparation

Thanks

The β parameter

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

$$\int_T I(t)\,dt = 15.44\cdot 10^6\,C$$

$$D = 0.025\,m$$

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

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

$$s = 10\,m^2\cdot kg^{-1}$$

$$z = 1.5\cdot 10^{-3}\,m$$

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

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

The β parameter

Ignatiev & Kuzmin model → **creation and destruction operators connect 3 states**

- ***the vacuum state*** $|0\rangle$
- ***the single occupancy state*** $|1\rangle$
- ***the <u>non-standard</u> double occupancy state*** $|2\rangle$

through the following relations:

$$a^+|0|1 \qquad a|0\,0$$

$$a|1$$

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

The parameter β quantifies the degree of violation in the transition.

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

It is very small and for <u>$\beta \rightarrow 0$</u> we recover the <u>Fermi - Dirac statistic</u>.

The β parameter

this β can be simply related to the q parameter of the quon theory of Greenberg and Mohapatra

$$\frac{1}{2}\beta^2 = \frac{1+q}{2}$$

quon algebra is a sort of weighted average between fermion and boson algebra:

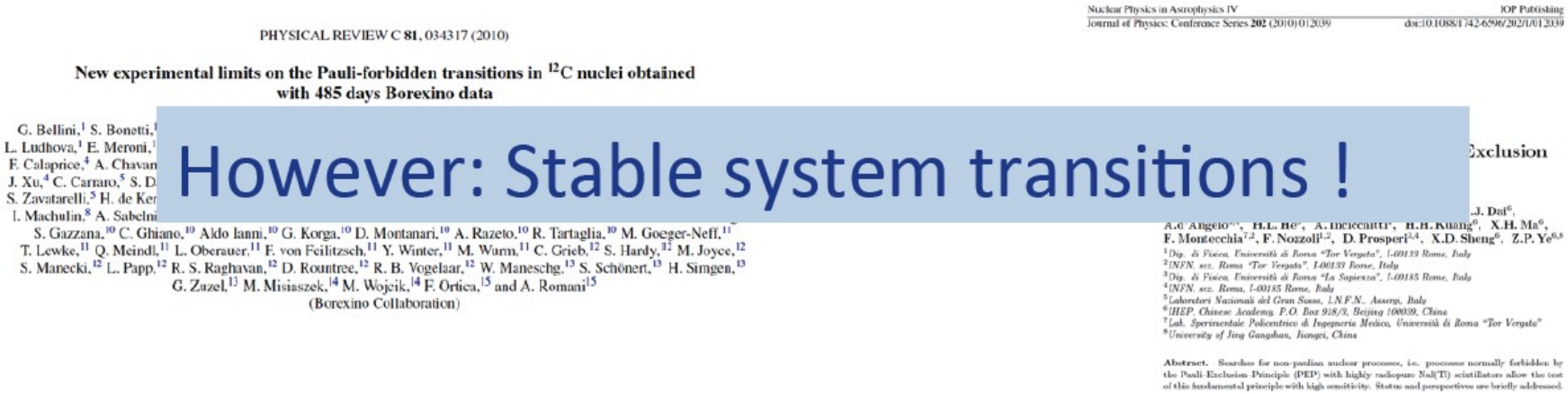
$$\frac{1+q}{2}\left[a_k, a_l^+\right]_- + \frac{1-q}{2}\left[a_k, a_l^+\right]_+ = \delta_{kl}$$

or also

$$a_k a_l^+ - q a_l^+ a_k = \delta_{kl}$$

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	$\frac{\beta^2}{2} < 1,28 \cdot 10^{-47}$	R. Bernabei et al., Eur. Phys. J. C62 (2009) 327
	$Ge \rightarrow Ge + \gamma$ (K_α)	MALBEK	$\frac{\beta^2}{2} < 2,92 \cdot 10^{-47}$	N.Abgrall et al., Eur. Phys. J. C (2016) 76.



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

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

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F. Calaprice,[4] A. Chavan
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]
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Nuclear Physics in Astrophysics IV IOP Publishing
Journal of Physics: Conference Series **202** (2010) 012039 doi:10.1088/1742-6596/202/1/012039

However: Stable system transitions !

Exclusion

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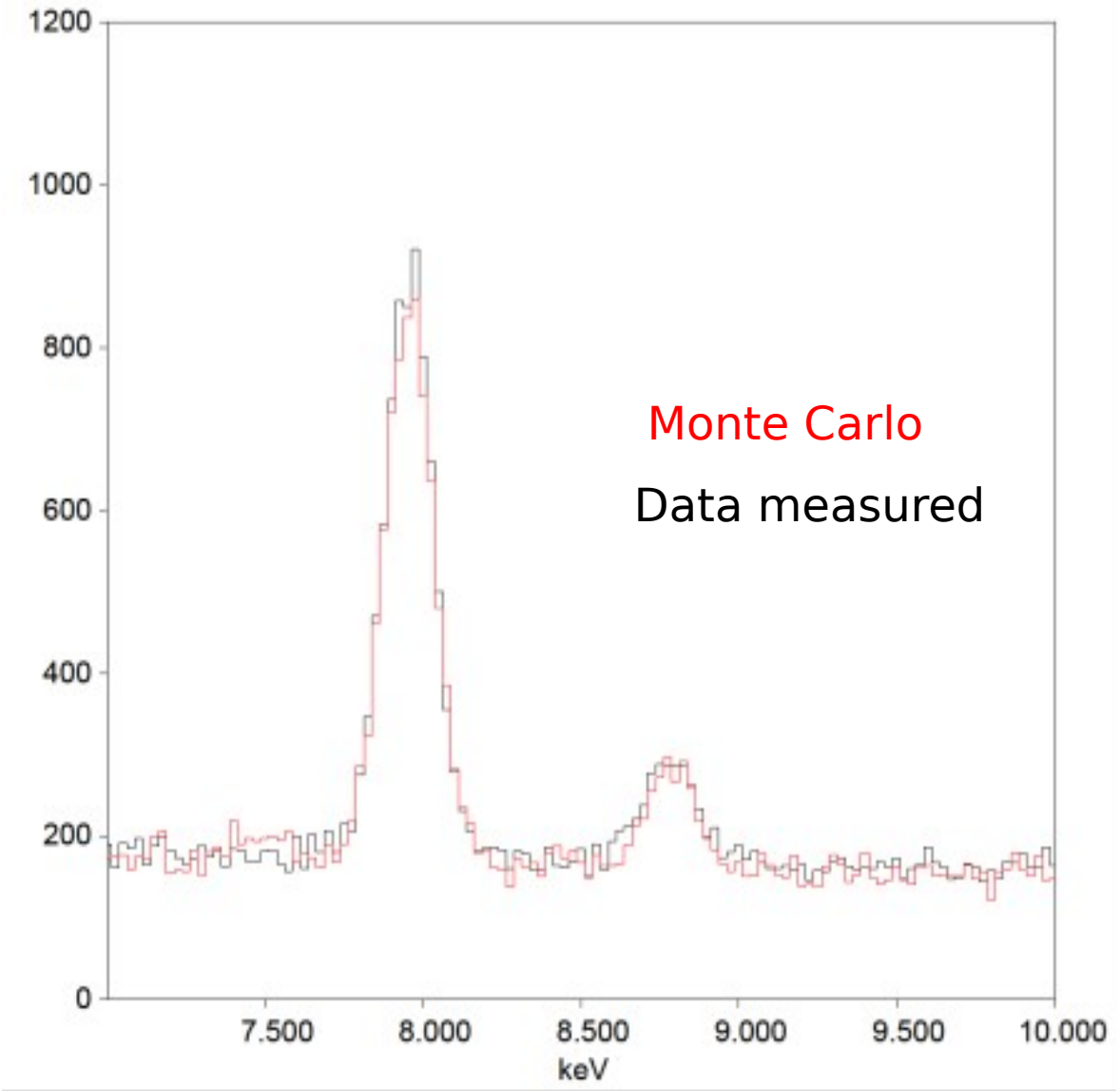
Abstract. Searches for non-paulian nuclear processes, i.e. processes normally forbidden by the Pauli-Exclusion-Principle (PEP) with highly radiopure NaI(Tl) scintillators allow the test of this fundamental principle with high sensitivity. Status and perspectives are briefly addressed.

PEP Tests with atomic transitions

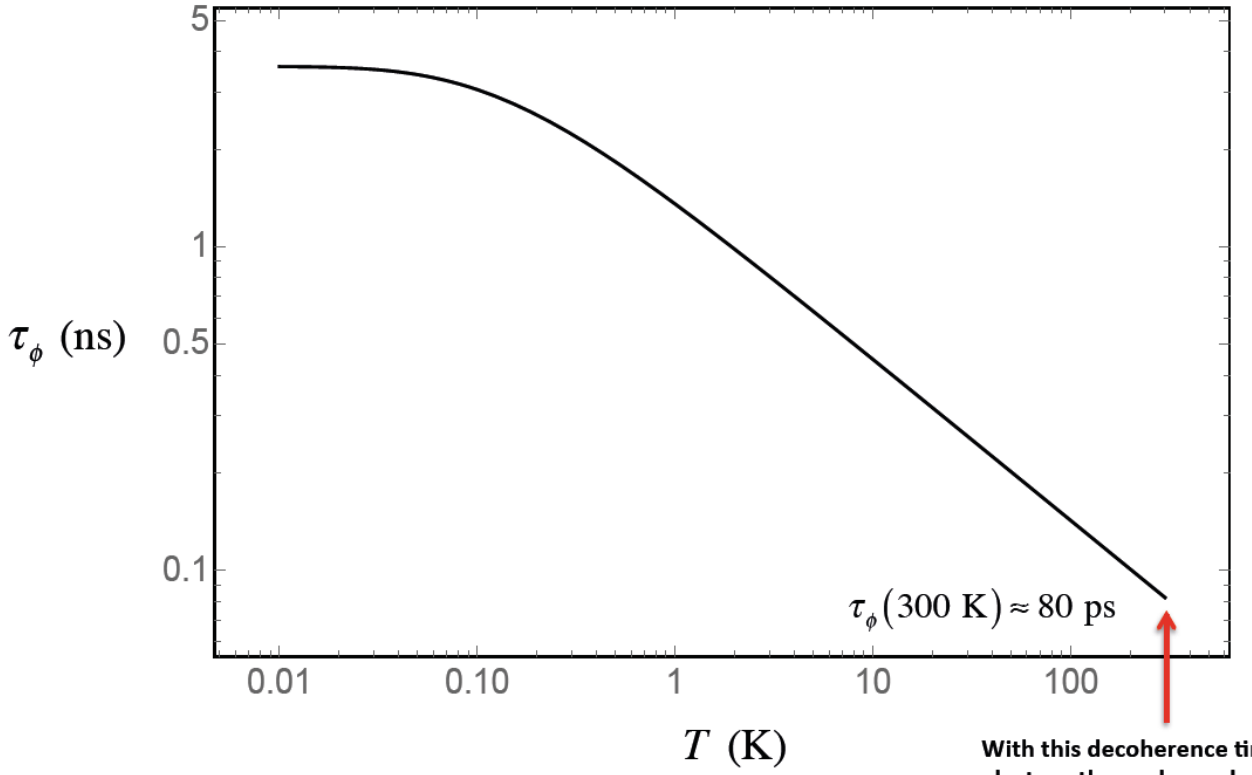
From S.R. Elliott et al., Found. Phys. 42 (2012) 1015

Process	Type	Experimental limit	$\frac{1}{2}\beta^2$ limit	
Atomic transitions				
$\beta^- + \mathrm{Pb} \rightarrow \check{\mathrm{P}}\mathrm{b}$	Ia		3×10^{-2}	Recently created fermions interacting with system
$e^-_{pp} + \mathrm{Ge} \rightarrow \check{\mathrm{G}}\mathrm{e}$	Ia		1.4×10^{-3}	
$e^-_I + \mathrm{Cu} \rightarrow \check{\mathrm{C}}\mathrm{u}$	II		1.7×10^{-26}	
$e^-_I + \mathrm{Cu} \rightarrow \check{\mathrm{C}}\mathrm{u}$	II		4.5×10^{-28}	Distant fermions interacting with system
$e^-_I + \mathrm{Cu} \rightarrow \check{\mathrm{C}}\mathrm{u}$	II		6.0×10^{-29}	
$e^-_I + \mathrm{Pb} \rightarrow \check{\mathrm{P}}\mathrm{b}$	II		1.5×10^{-27}	
$e^-_f + \mathrm{Pb} \rightarrow \check{\mathrm{P}}\mathrm{b}$	IIa		2.6×10^{-39}	Stable system transition
$\mathrm{I} \rightarrow \check{\mathrm{I}} + \text{X-ray}$	III	$\tau > 2 \times 10^{27}$ sec	3×10^{-44}	
$\mathrm{I} \rightarrow \check{\mathrm{I}} + \text{X-ray}$	III	$\tau > 4.7 \times 10^{30}$ sec	6.5×10^{-46}	

LNGS Background studies with Monte-Carlo



Electron decoherence time at room temperature



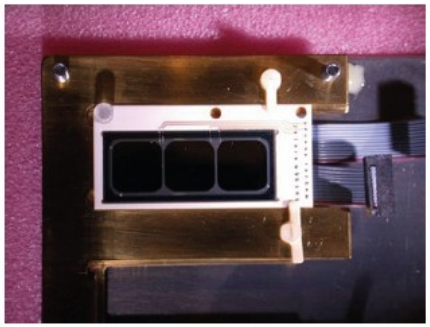
E. Milotti, Talk, May 29, 2015, Vienna

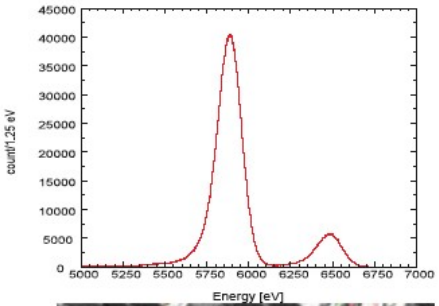
With this decoherence time and the electron thermal speed we find a decoherence length of about 10 μm

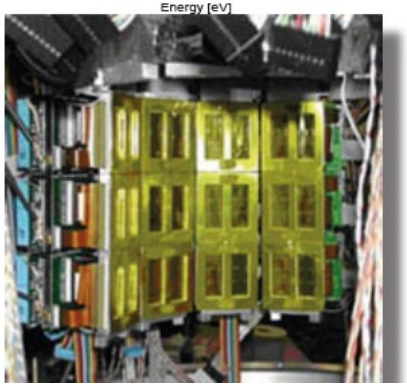
The conclusion is that after a time of the order of the *decoherence time* the electron wavefunctions are effectively decoupled and the environment acts on electrons by enforcing an effective locality.

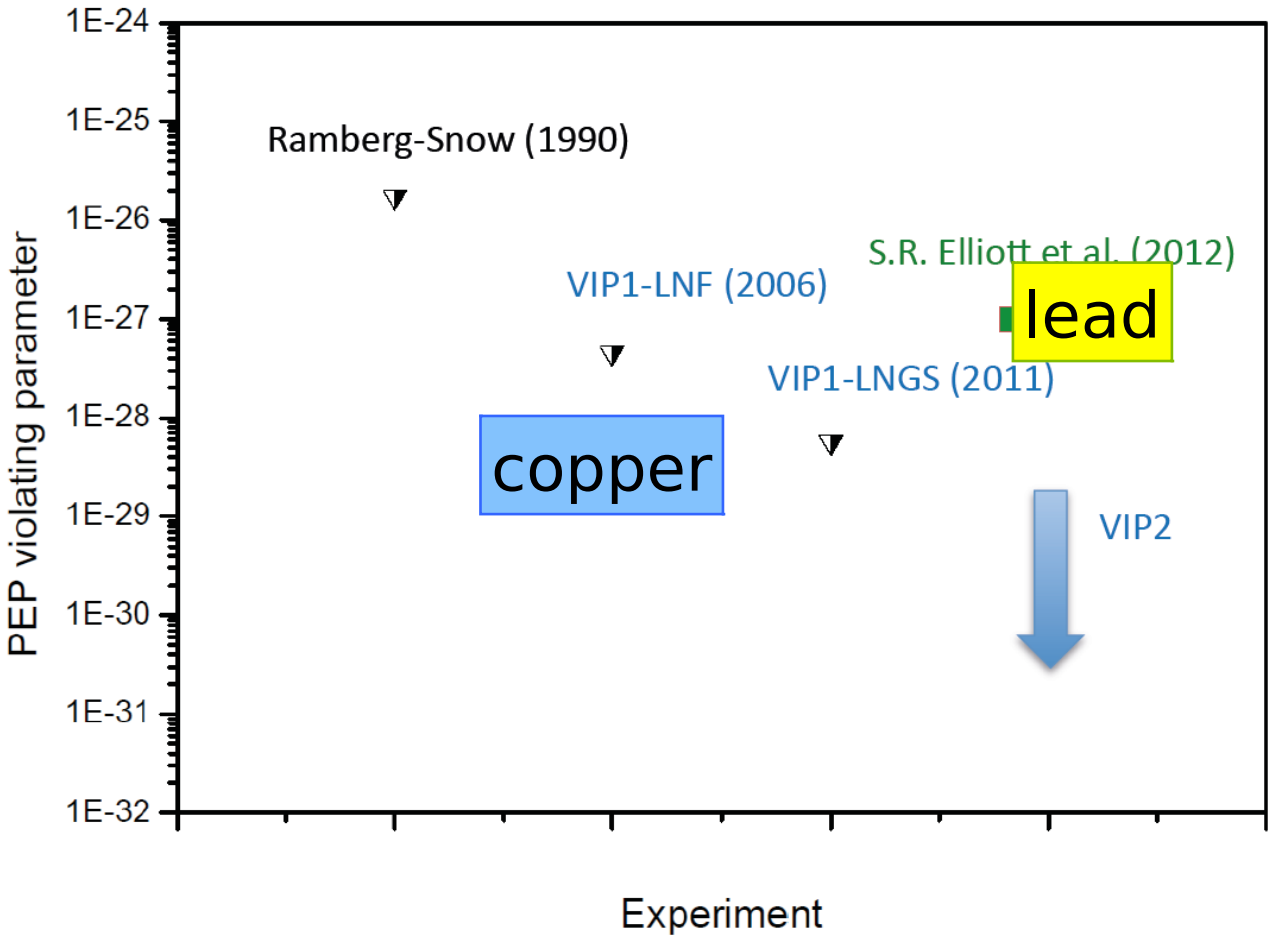
Improved experiment VIP2

- 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

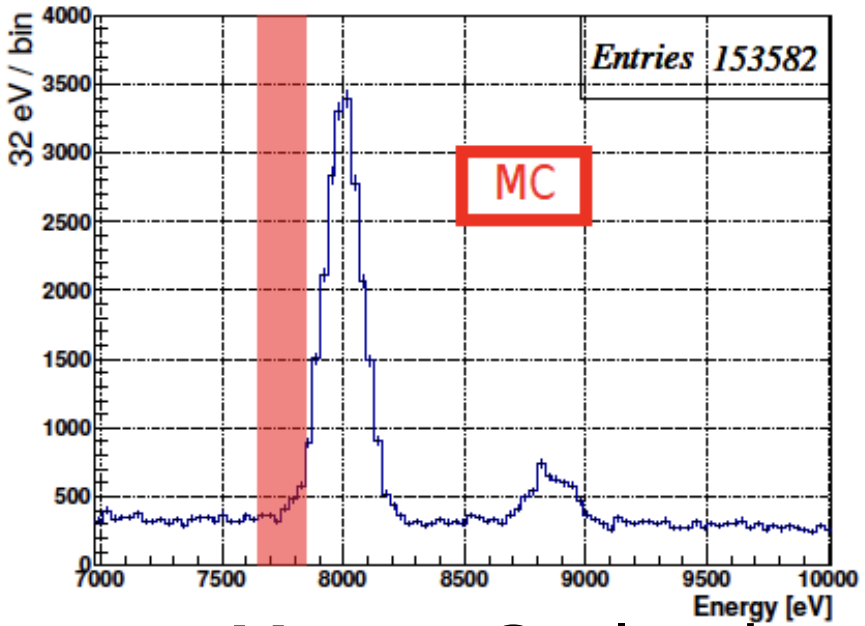


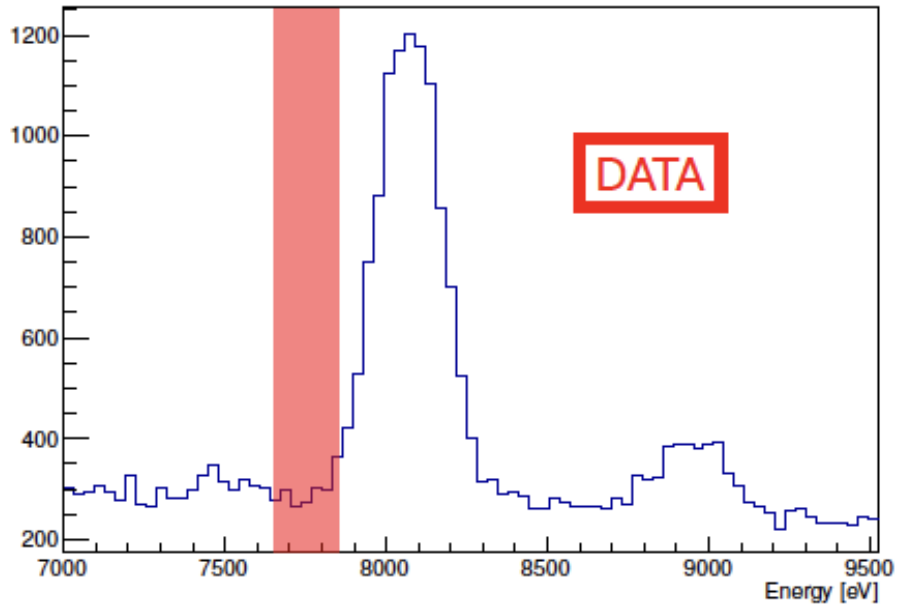





1E-24
1E-25
1E-26
1E-27
1E-28
1E-29
1E-30
1E-31
1E-32
PEP violating parameter
Ramberg-Snow (1990)
VIP1-LNF (2006)
S.R. Elliott et al. (2012)
lead
VIP1-LNGS (2011)
copper
VIP2
Experiment

Comparison MC and Data @ LNGS

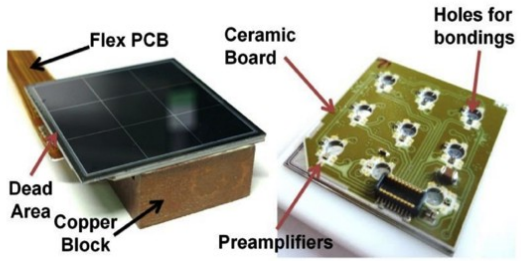
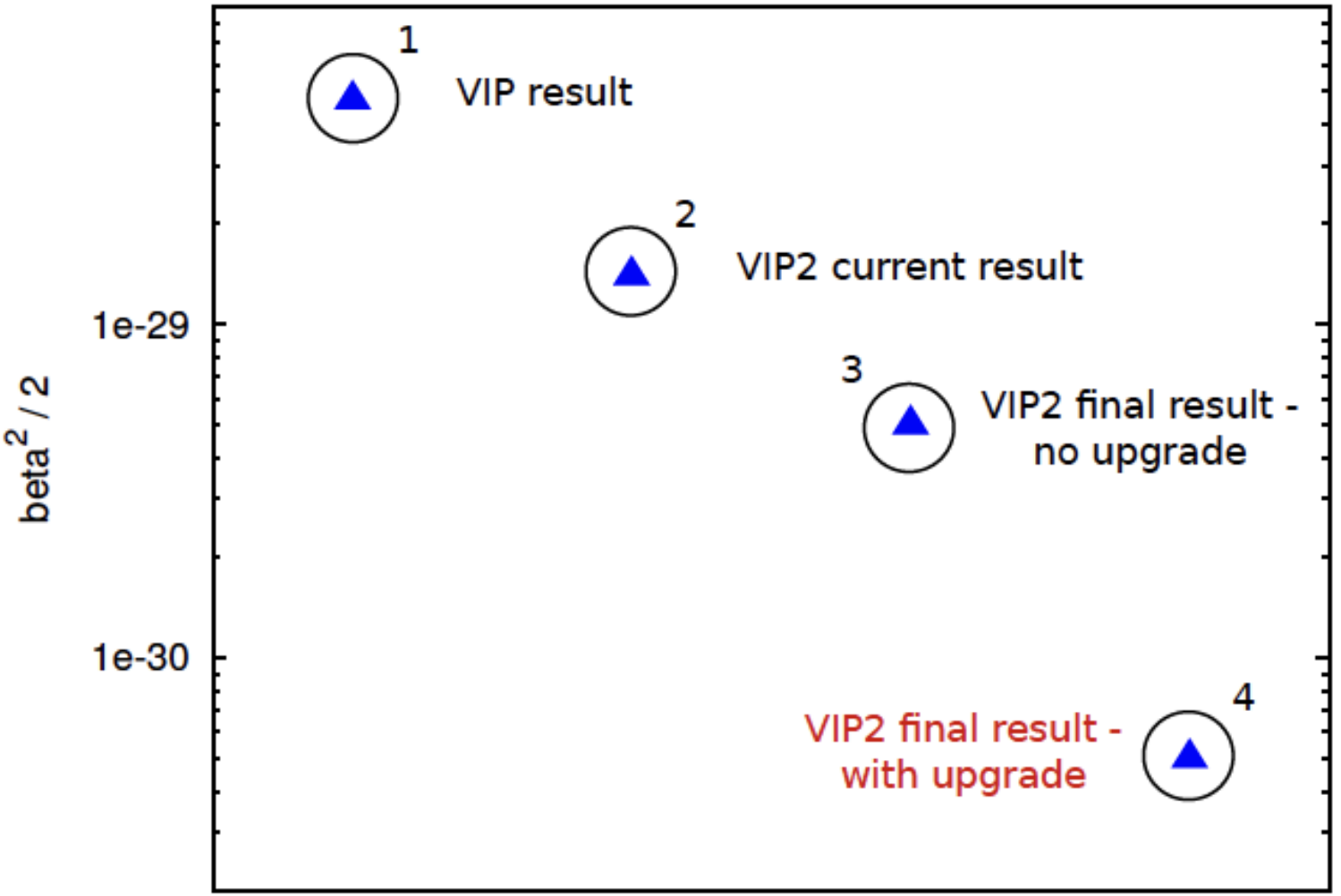




Monte Carlo simulation of 30 days data taking and actual data taken in 30 days

Future Research Plan

- Installation of part of the passive shielding
- New SDD detector system with new copper targe
- In 2017 new copper target with new SDDs will be installed
- Optimized shielding with data taking of about 3 years (i.e. approx. 2020)
- Goal after 3 years data taking with and without current
  → 10^2 improvement of VIP limit



Toward the final result