ROGUE ELECTRON: A PHYSIC WARS STORY

THE VIP2 EXPERIMENT IS LOOKING FOR THE REBEL ELECTRON WHICH COULD VIOLATE THE PAULI EXCLUSION PRINCIPLE

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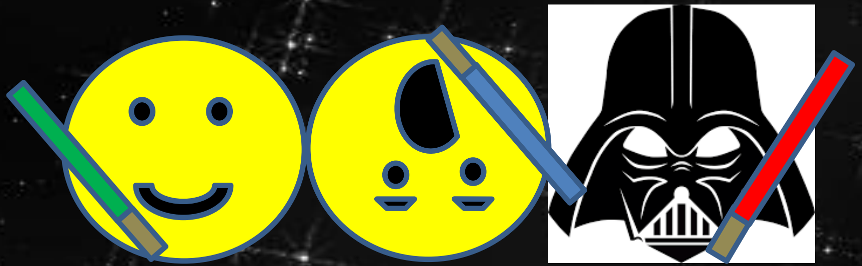

INSPYRE - 2nd APRIL 2019

IN A WORLD FULL OF ELECTRONS RULED OUT BY THE PAULI EXCLUSION PRINCIPLE THERE COULD BE A LITTLE GROUP OF REBEL ELECTRONS WHICH JUMP AMONG ATOMS.

THE NOBEL PRIZE FOR PHYSICS W. E. PAULI DECLARED IN 1945:
"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."*

IN 2016 A SMALL GROUP OF PHYSICISTS BUILT A STRONG MACHINE WHICH COULD GIVE THEM ENOUGH POWER TO IDENTIFY THESE REBELS.

THIS EXPERIMENT IS CALLED *VIP2 (Violation of Pauli)*.
THE REBEL ELECTRON HUNT CONTINUES….

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

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 VIP2

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 VIP2

The experimental method of VIP2 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

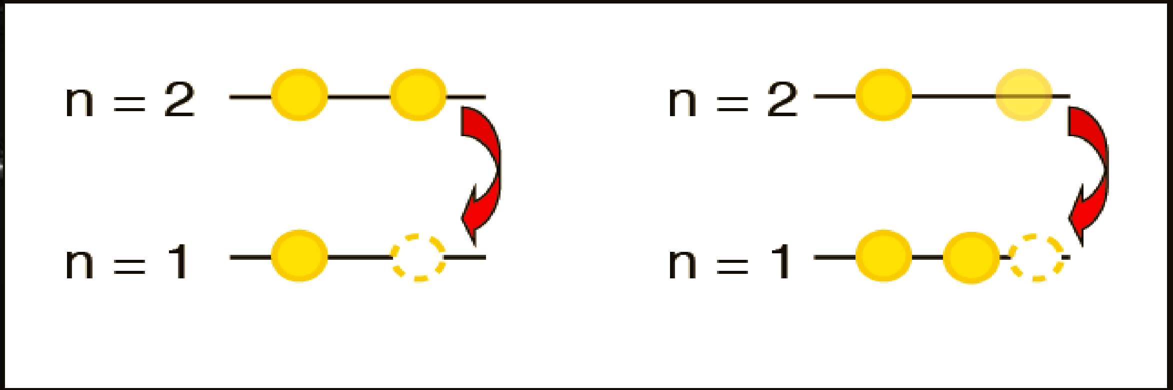
C. Curceanu, L. De Paolis et al., "Evaluation of the X-ray transition energy for the Pauli-principle-violating atomic transitions in several elements by using Dirac-Fock method", 2013, INFN-13-21/LNF.

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.

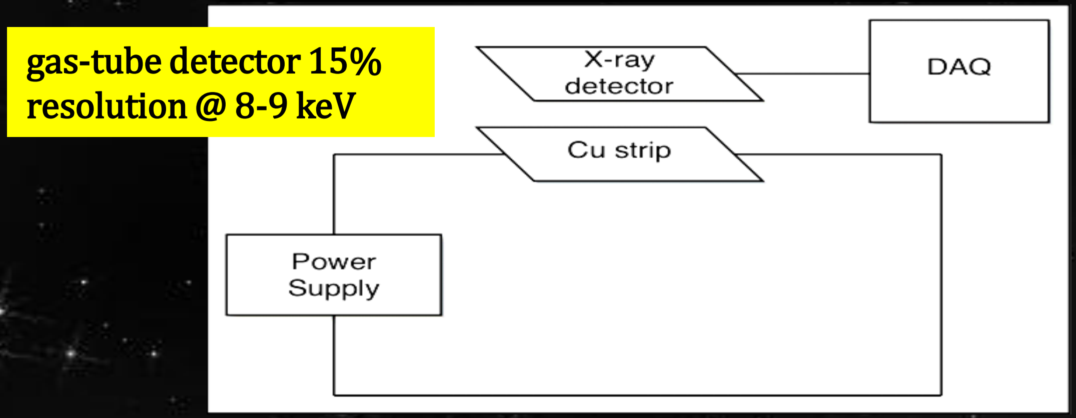
The non-Paulian transition to level 1S produces the emission of a PEP violating X-ray.

2. Historical Goals: Ramberg and Snow(RS) experiment

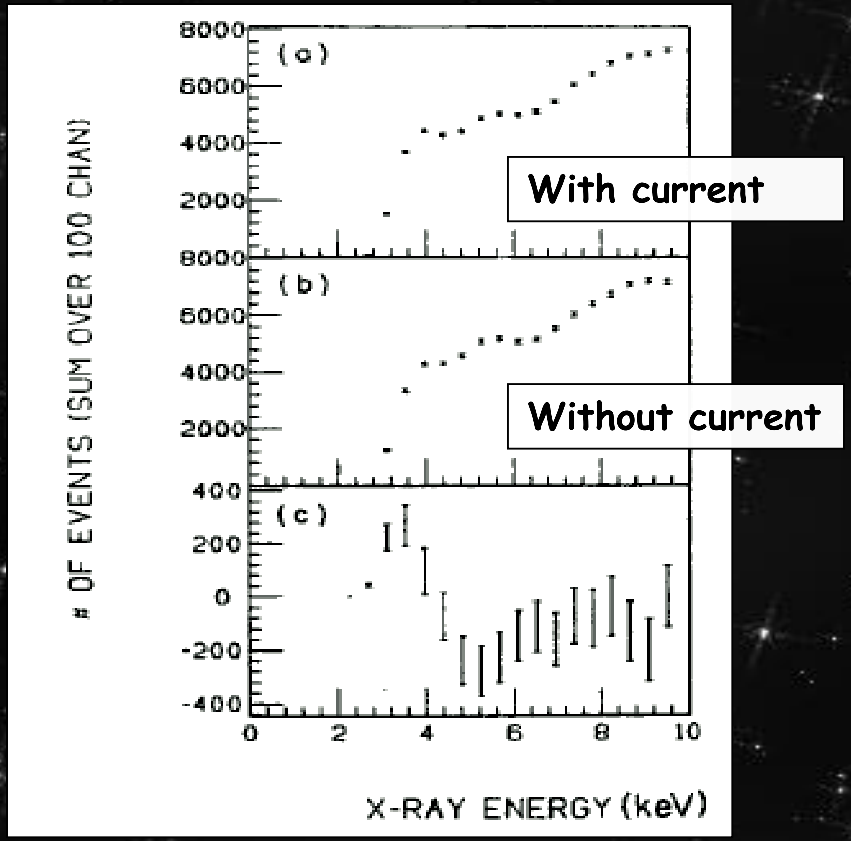
[Phys. Lett. B238 (1990) – 438]

In 1988 Ramberg and Snow performed a dedicated experiment which sought to identify anomalous transition, forbidden by PEP, of electrons in a copper target crossed by a current.

Schematization of the RS apparatus



Spectra got in 2 month of data taking



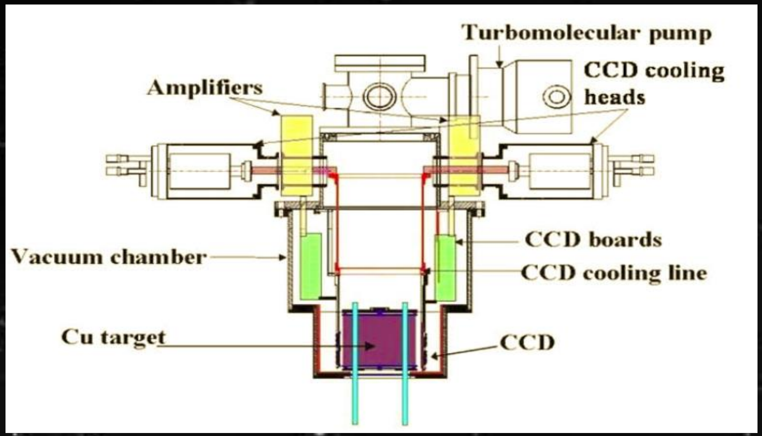
The upper limit to the probability of violation of PEP for electrons in copper calculated by RS experiment is:

$$\frac{\beta^2}{2} < 1.7 \times 10^{-26}$$

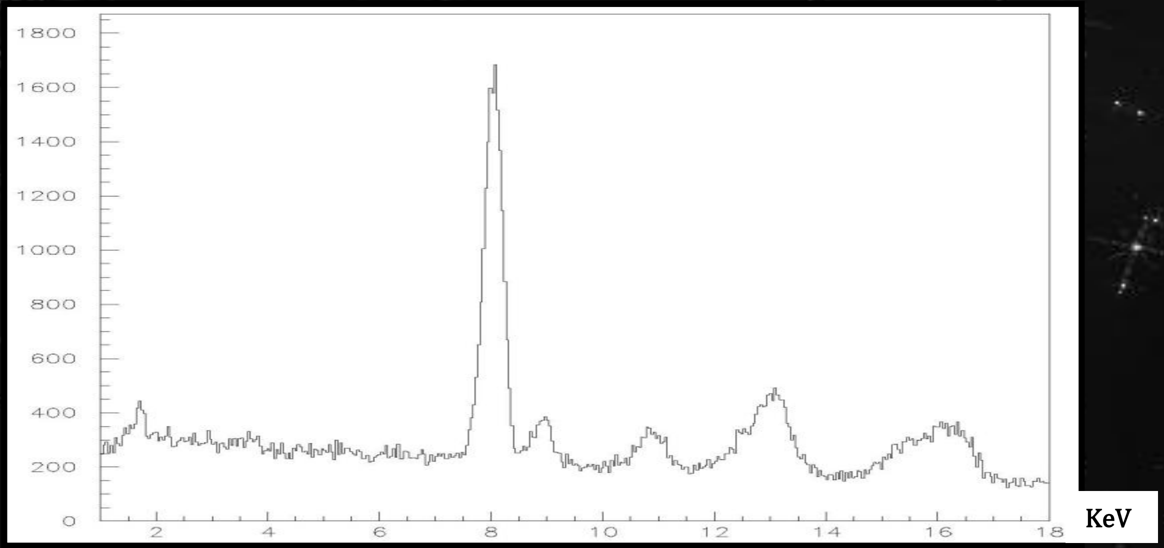
2. Historical Goals: The VIP experiment

Improvements made respect to RS experiment:

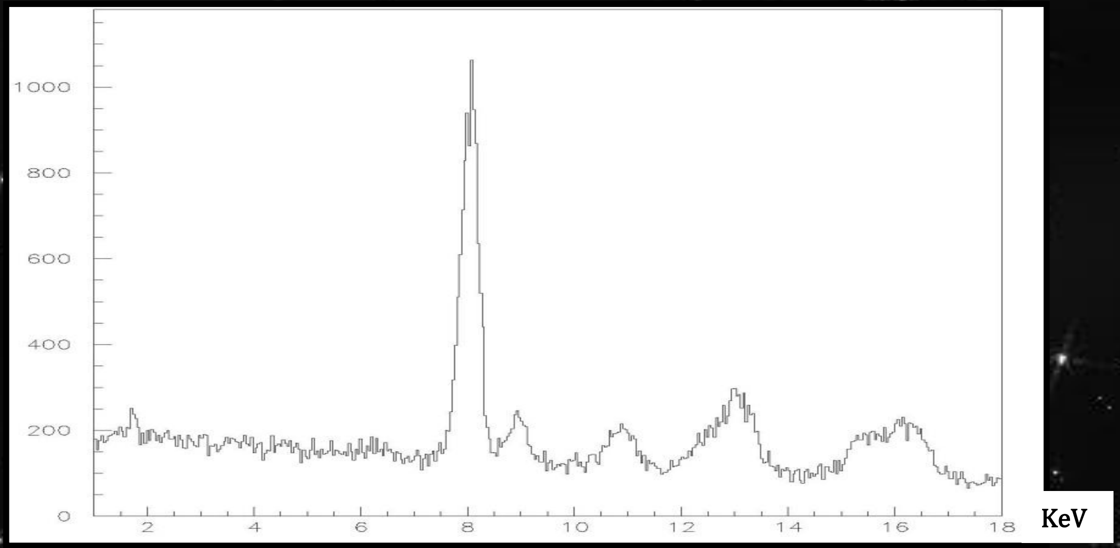
- More sensitive X-ray detectors covering more surface: Charge Coupled Device (CCD)
- A cleaner and low-background experimental area (LNGS)
- A better statistic due to the longer time taken.



Spectrum with current: I = 40 A

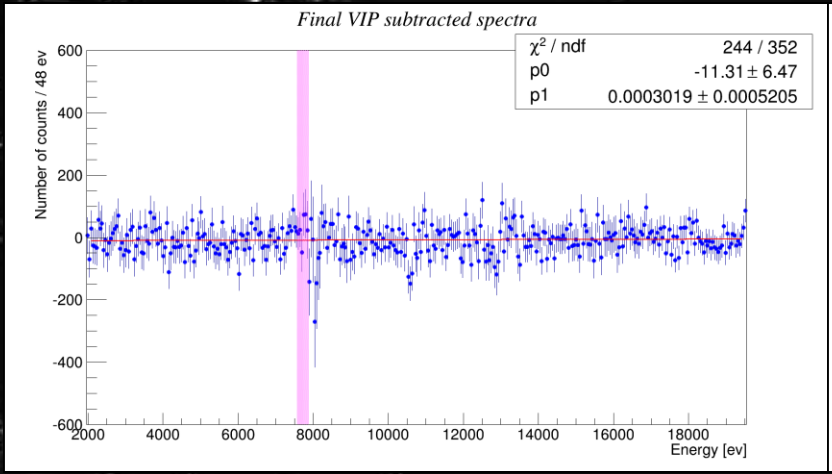


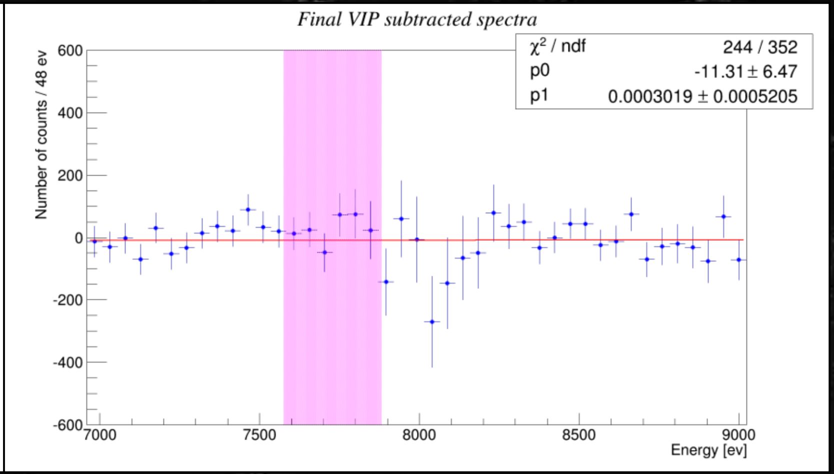
Spectrum of background: I = 0 A



2. Historical Goals: The VIP experiment

Subtracting spectra, the one acquired with current of 40 A on target and the other one acquired without current on target, has been possible to extract the number of X-rays measured with an energy inside the range of interest (ROI) for a possible violation of PEP.





FWHM = Γ = 300 eV

ROI: [7585,7895]

$N_X + \varepsilon_X = 37 \pm 146$

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

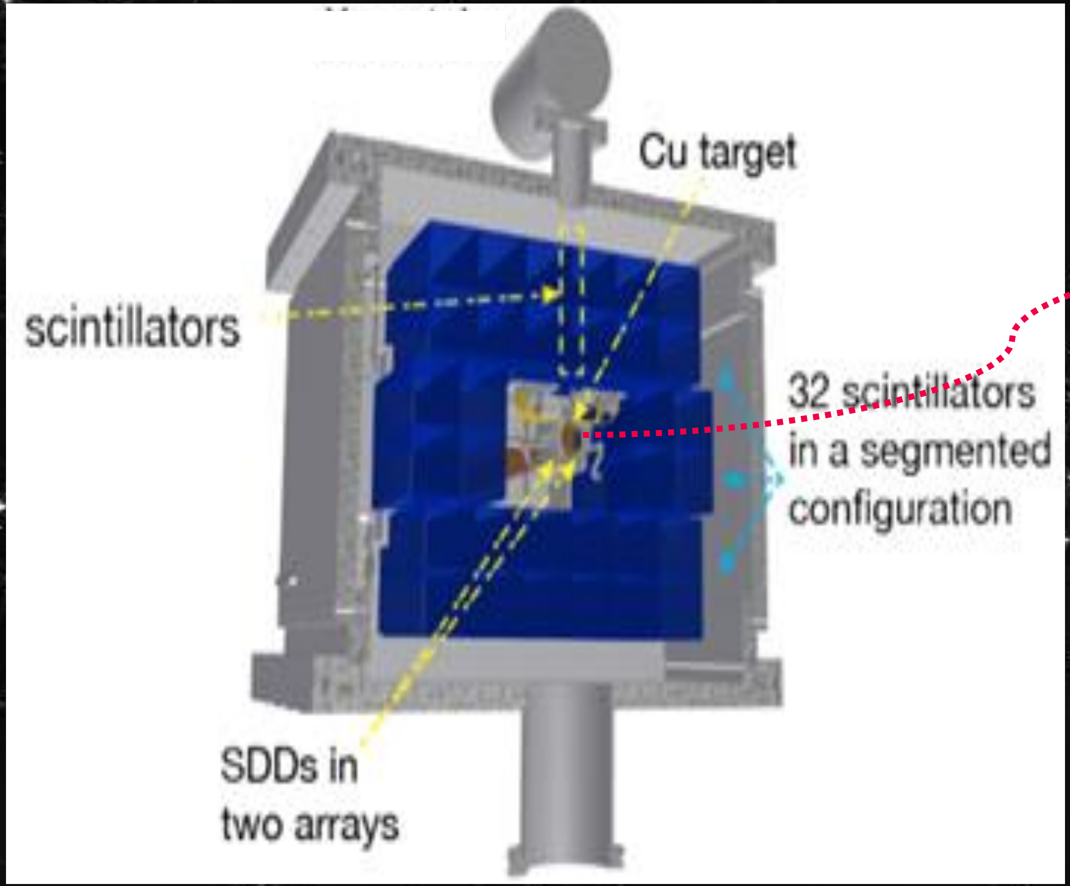
The VIP experiment has reduced the experimental limit on the violation of PEP for electrons in copper, thanks to the CCD detectors more sensitive than RS gas detectors and to the Gran Sasso mountain which broke down a large amount of background, until…

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

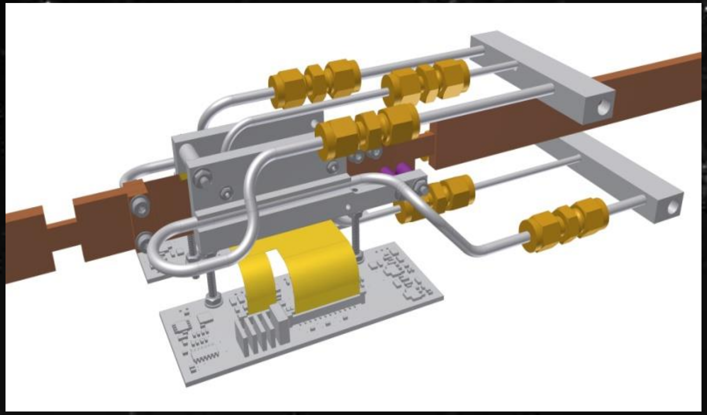
Curceanu, C. et al.: J. Phys. 306, 012036 (2011)

3. The VIP2 experiment: purpose and apparatus.

Schematization of the VIP2 chamber



Target of VIP2

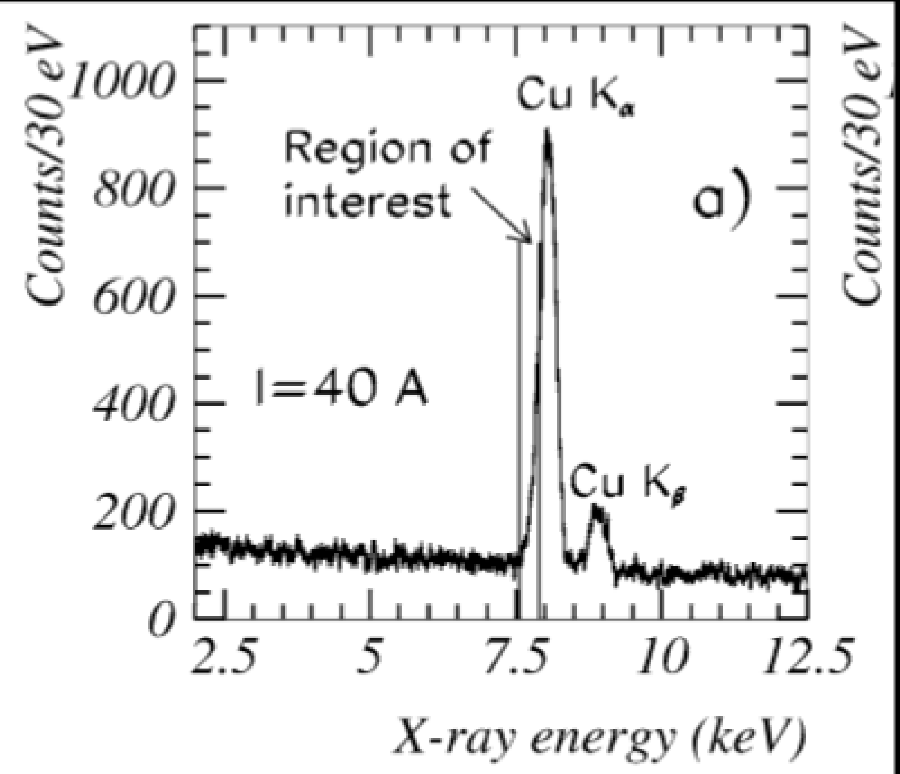


Characteristics of the target: the 2 strips (10 cm x 1 cm x 50 μm) are connected to an external generator by 2 thin copper bars. Due to the Joule effect, the current is heats the target to 20 ° C.
A water circuit cools them so that the temperature of the detectors does not increase by more than 2K.

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

From CCD to SDD – Energy resolution

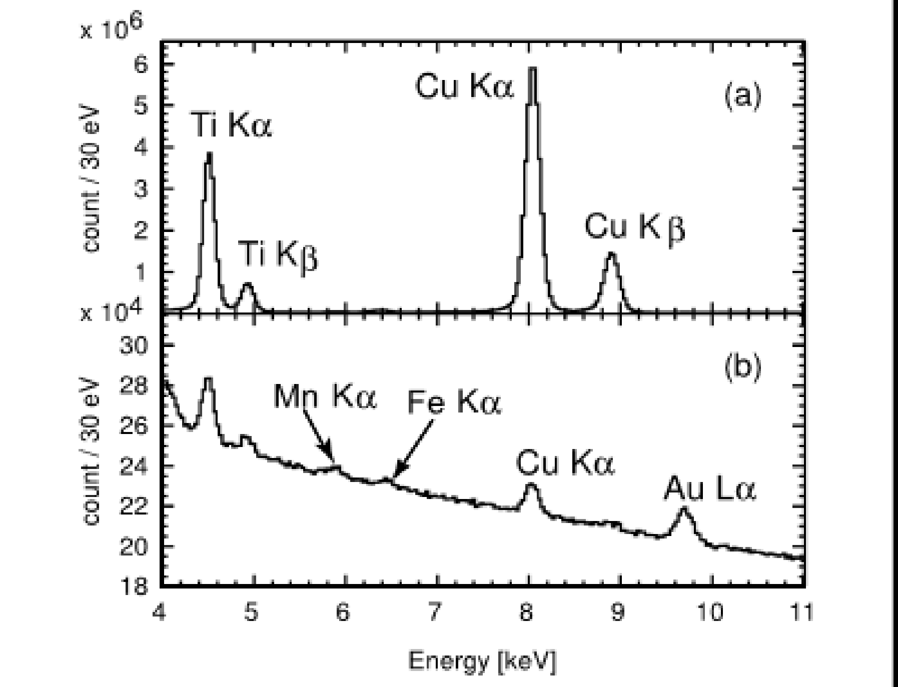
VIP



S. Bartalucci, et. al, Physics Letters B **641**, 18 (2006).

FWHM 340 eV
@ 8 keV

SIDDHARTA



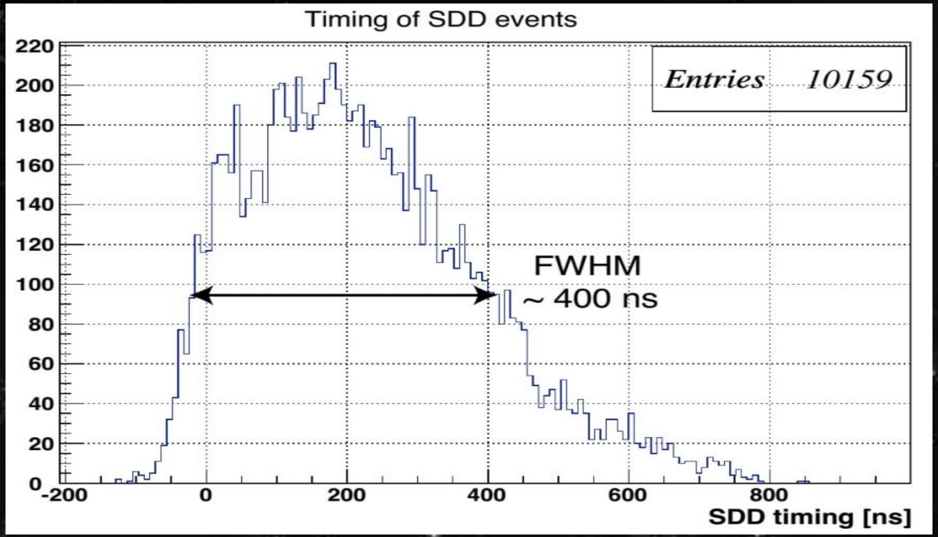
M. Bazzi, Physics Letters B 697 (2011) 199–202

FWHM 170 eV
@ 8 keV

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

In the apparatus the SDDs are organized in 2 chips containing 3 cells with 100 mm2 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.

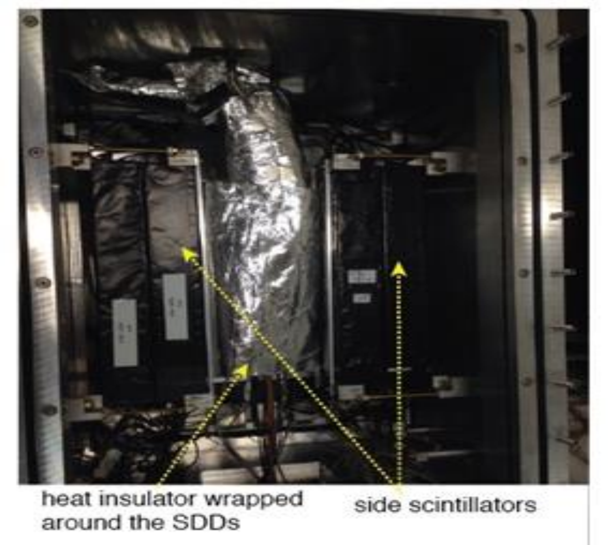
The energy resolution was tested with a Fe-55 source through a 25 μm thick Ti-plate. The lines of the K series of Mn and Ti are used to calibrate the spectrum and measure the energy resolution at 6 keV (rate of about 2 Hz). This test resulted in a **resolution of about 150 eV at 6 KeV.**

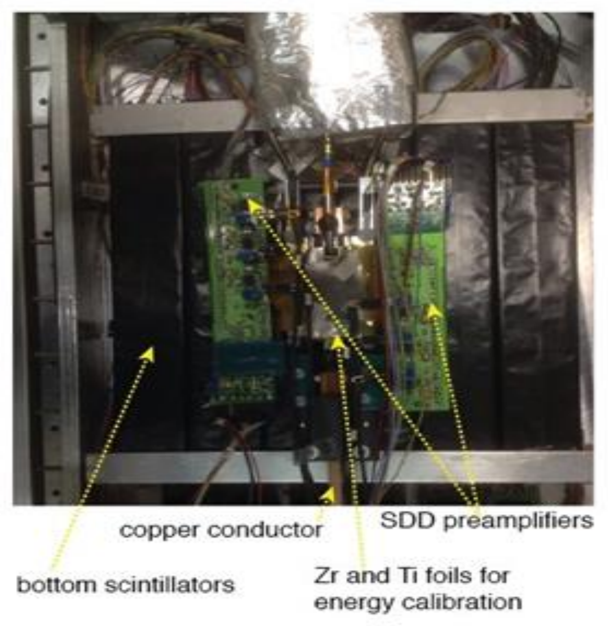


SDDs provide information on radiation energy and timing -> measurement performed with respect to the scintillator trigger: **400 ns (FWHM).**

SUFFICIENT TEMPORAL RESOLUTION TO DISCRIMINATE THE BACKGOUND EVENTS

3. 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 45x3x3 cm and covering a solid angle > 90% compared to the target.

The scintillators are read by pairs of SiPM (with 3x3 cm2 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

3. The VIP2 experiment: future goal

Improvents with regard to VIP:

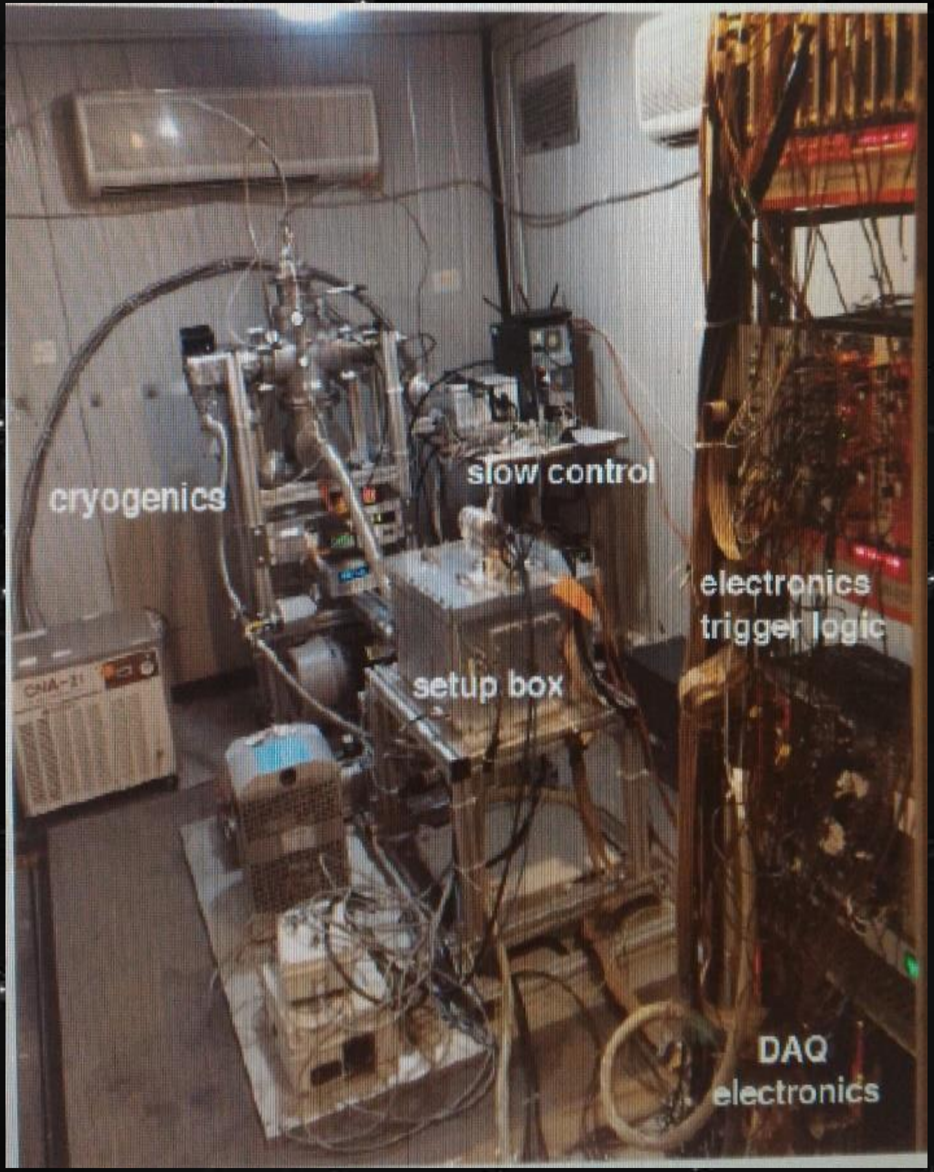
- More compact system → improves acceptance
- New target → 2 strips 10 cm x 1 cm x 50 μm
- Different cooling system for the target (water)
- Current flowing into the target > 100 A
- Nitrogen flushing to reduce radon in barrack
- New SDD detectors with better resolution, cooled with liquid Argon (110 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:

$$\frac{\beta^2}{2} < 4.7\times10^{-29} \rightarrow 10^{-31}$$

3. The VIP2 experiment: photo of the apparatus



4. NEW upper LIMIT for the PEP violation probability

Subtracting the spectra got with data taking until July 2017:

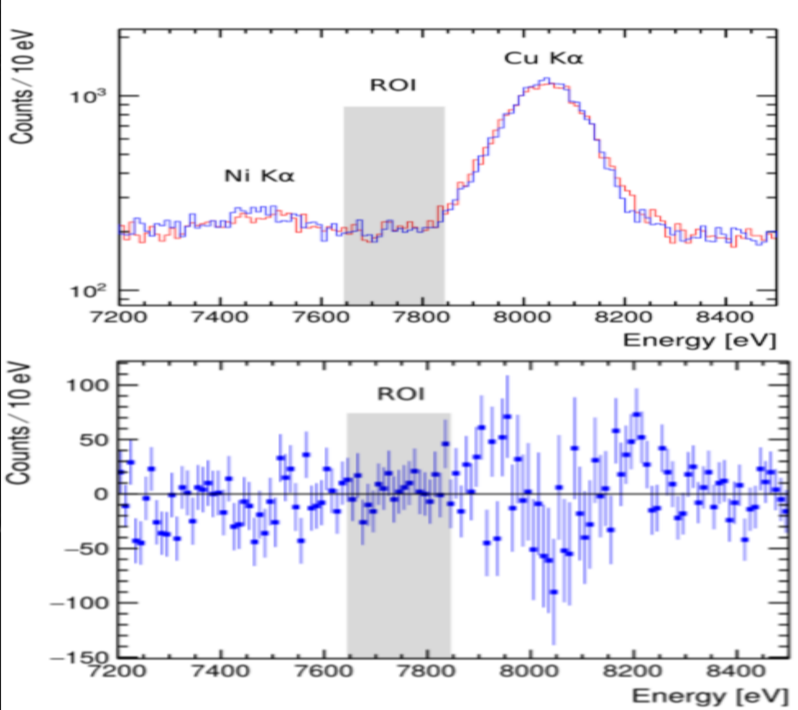
$\Delta N_x = 97 \pm 91$ Normalized to 81 days

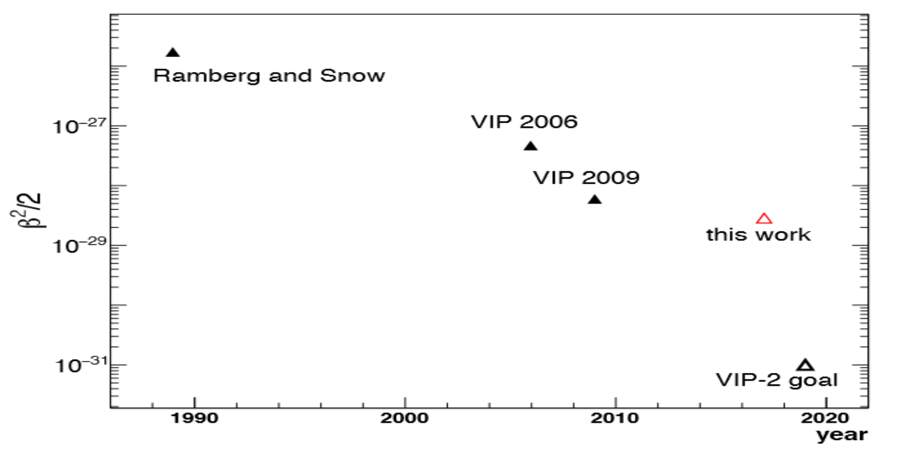
$$\Delta N_x \geq \frac{\beta^2}{2} N_{new} \frac{1}{10} N_{scatt} \times Eff_{riv} \rightarrow \frac{\beta^2}{2} \leq 1.87 \times 10^{-29}$$

Confidence Level: 99.73%

P. Andreas et al., «Test of the Pauli Exclusion Principle for Electrons in the Gran Sasso Underground Laboratory», PHD Thesis, 2018.

We note how with VIP2 we have managed, in the space of about three months 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.





CONCLUSION

VIP2: MAY THE FORCE BE WITH YOU

W. E. PAULI

Thank you all for your attention !!

Modello di Ignatiev & Kuzmin

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

The operators of creation and destruction allow 3 states:

- $|0\rangle$ **vuoto**
- $|1\rangle$ **stato di singola occupazione**
- $|2\rangle$ **stato <u>non-standard</u> di doppia occupazione (due fermioni hanno lo stesso stato)**

attraverso le relazioni:

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

The parameter β expresses the degree of violation in the transition

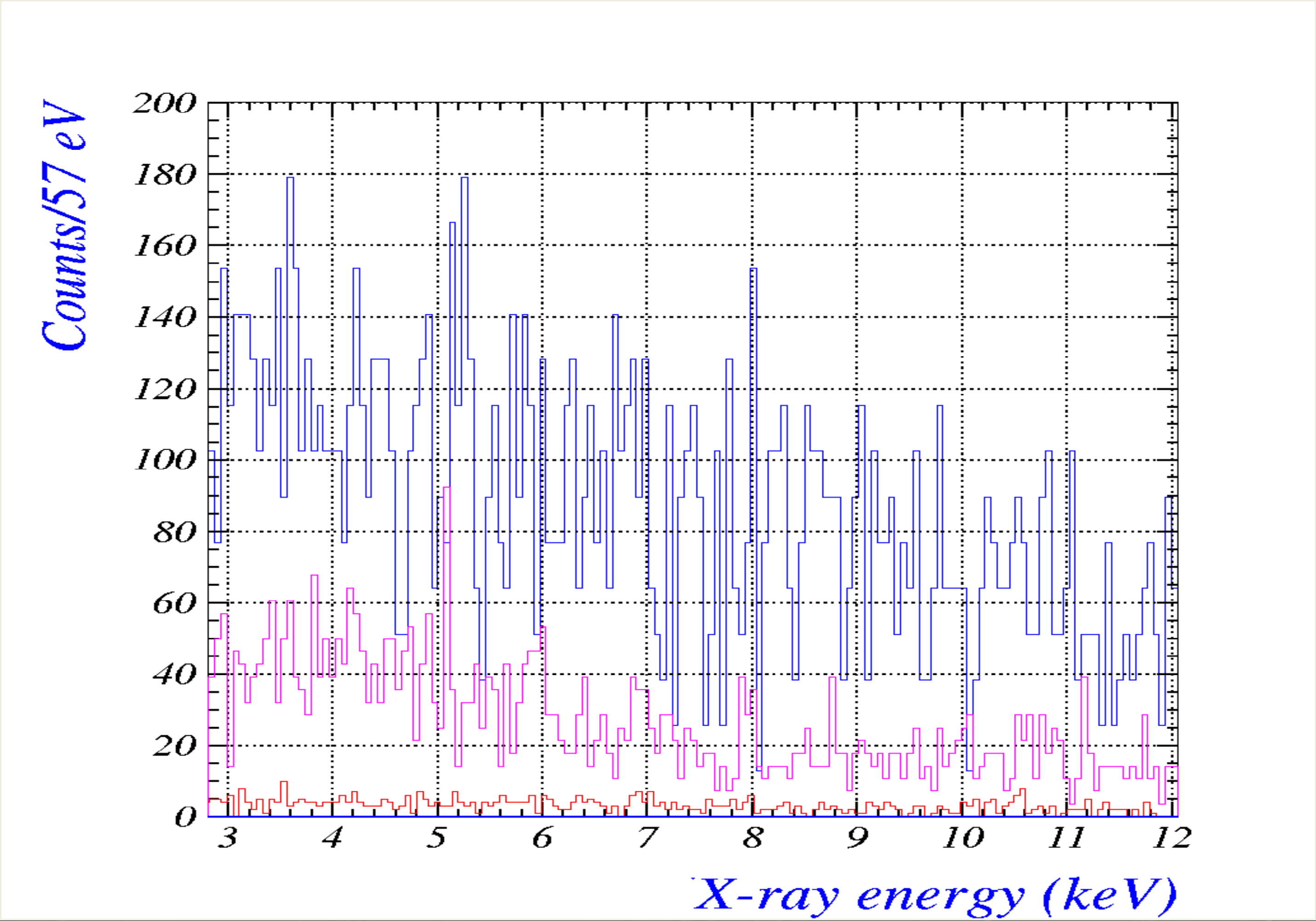
$|1\rangle \rightarrow |2\rangle$

Non-Paulian atoms having an abnormal distribution of electrons on the orbitals

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

Why at LNGS?

Test setup with 2 CCD –
Normalized distribution



— LNF no shielding

— LNF with shielding

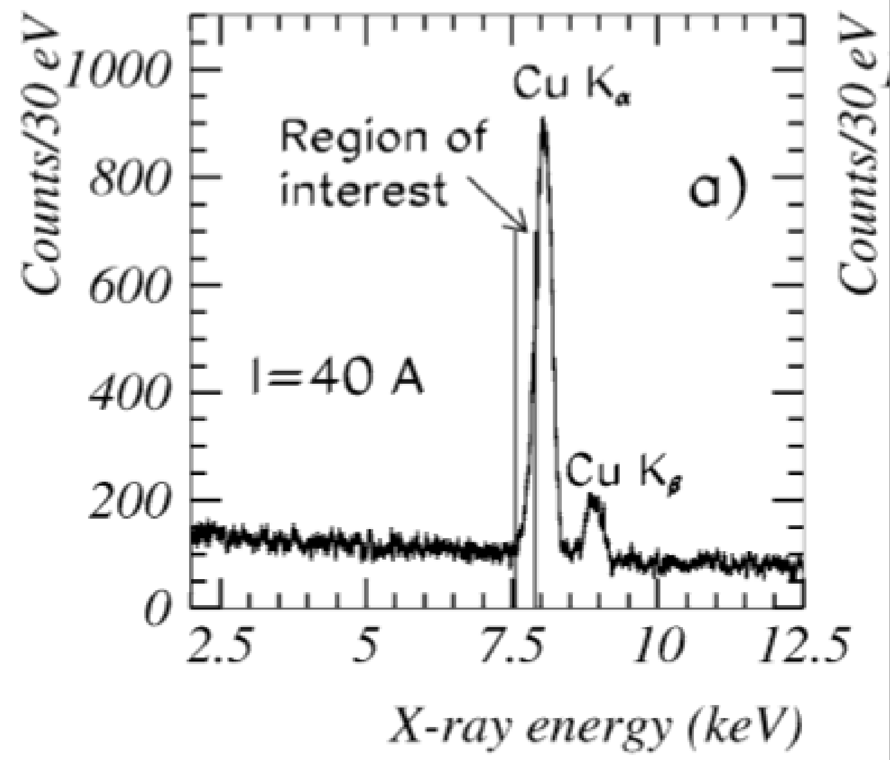
— LNGS with shielding

The background is reduced of a factor of <u>~ 20</u>

VIP2: l’upgrade di VIP

From CCD to SDD – Energy resolution

VIP



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FWHM 340 eV
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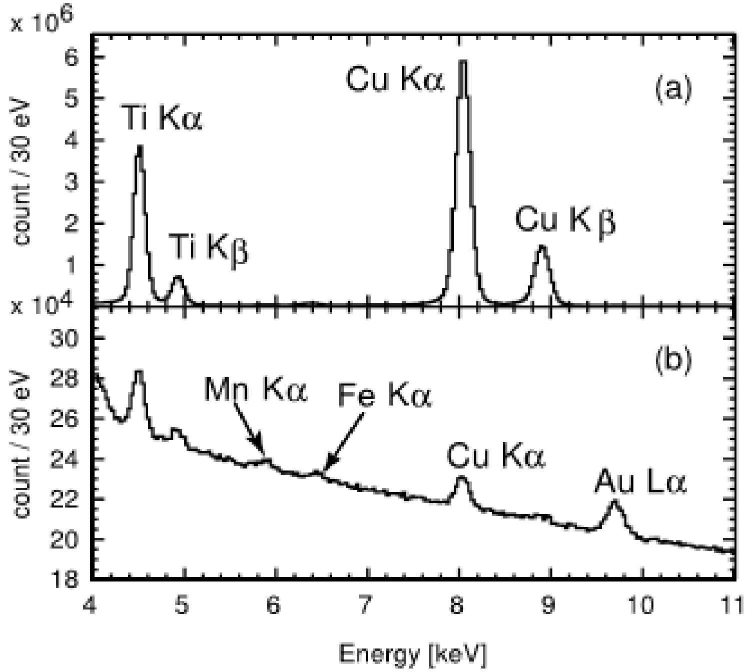

M. Bazzi, Physics Letters B 697 (2011) 199–202

FWHM 170 eV
@ 8 keV

Procedure for extracting the upper limit on the probability of violation of PEP in VIP2.

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

The detection efficiency factor was calculated using a Monte Carlo simulation based on Geant 4.10. The determined value is around 1% .

$$\Delta N_x = 97 \pm 91$$

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

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

D → Lenght of the electronic path (≈10 cm)

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

The probability of electron capture is greater than 1/10 of the scattering probability.

$$\frac{\beta^2}{2} \leq 1.87 \times 10^{-29}$$

Confidence level: 99.7%