**I am Luca De Paolis** and I was born in Rome on 06/09/1991

**In 2009,** I met Catalina Curceanu during the higher school and discovered Quantum Mechanics. I started a collaboration with Catalina’s group.

**In 2017,** I hold the Master degree in Physics at the University of Tor Vergata (Rome II) with the thesis: “Experimental study of the possible violation of the Pauli exclusion principle with the VIP2 experiment at the National Laboratories of Gran Sasso”.
Valutation: 110/110 cum laude.

**In 2021,** I hold the Ph.D. degree in Nuclear and Subnuclear Physics at the University of Tor Vergata (Rome II) with the thesis: “Study of relative yields from kaonic helium (3 and4) X-ray transitions measured by E62 at J-PARC”.
Valutation: Excellent cum laude.

**Since 2021,** I am PostDoc Researcher at the National Laboratories of Frascati, in Italy.

**Luca De Paolis is**

- Experimental researcher, data analyst, and data-taking coordinator for the SIDDHARTA2 experiment at LNF-INFN.
- Experimental researcher, data analyst for the E62 experiment at J-PARC (Japan).
- Experimental researcher, data analyst for the VIP2 experiment.
- Experimental researcher for the KAMEO project.
- Web Master and Web Designer for DISCO in the European STRONG-2020 project.

SCIENTIFIC PUBLICATIONS: 86 (6 as main author)
PERFORMED CONFERENCES: 23 (5 Posters, 17 Talks, 1 BEST POSTER WINNER)
ORGANIZED SYMPOSIA: 2


# ROGUE ELECTRON: A PHYSIC WARS STORY

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

Written and Directed by:

*Luca De Paolis*

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

CENTRO FERMI MUSEO STORICO DELLA FISICA E CENTRO STUDI E RICERCHE ENRICO FERMI

INFN Laboratori Nazionali del Gran Sasso

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."***

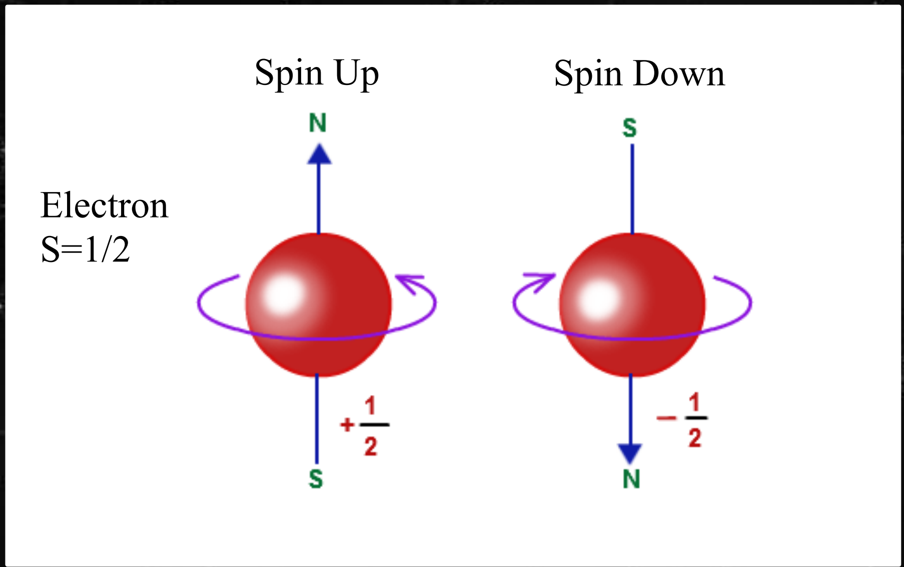
**IN 2016 A SMALL GROUP OF PHYSICISTS BUILT A STRONG MACHINE WHICH COULD GIVE THEM ENOUGH POWER TO IDENTIFY THESE REBELS.**

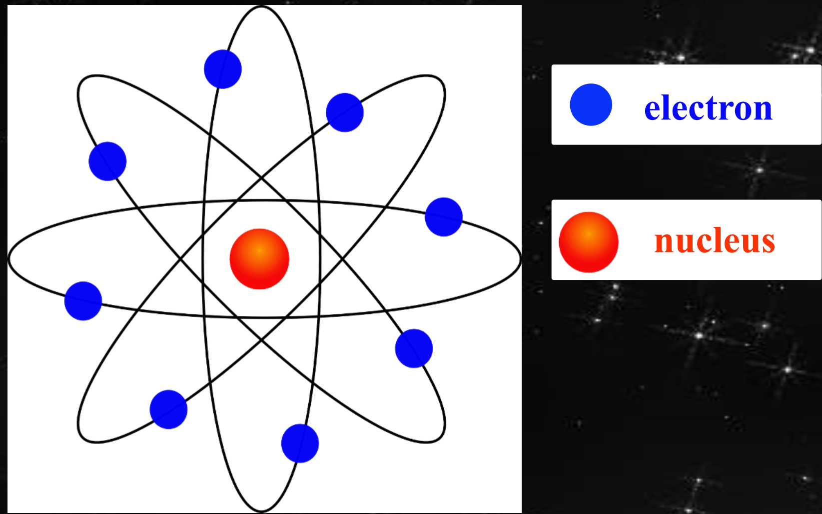
**THIS EXPERIMENT IS CALLED *VIP2 (Violation of Pauli)*.**
**THE REBEL ELECTRON HUNT CONTINUES….**

# The Pauli Exclusion Principle (PEP)

**In the atomic system, the Pauli Exclusion Principle (PEP) states that each atomic orbital cannot be occupied by more than two electrons having opposite spin.**

Electrons are fermions: particles with half-odd-integer spins s (1/2, 3/2 ….)




The spin is the intrinsic angular momentum of a particle.

# The Pauli Exclusion Principle (PEP)

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

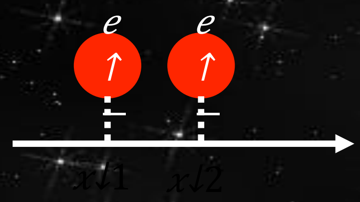
2) Bosonic and fermionic states have a different behavior in relation to the application of the exchange transformation (permutation) of identical particles: the former are symmetrical and the latter are anti- symmetrical

**HOW IS THIS CONNECTED WITH ATOMIC STRUCTURE?**

# The Pauli Exclusion Principle (PEP)

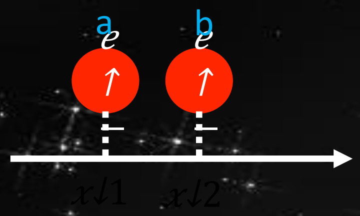
Fermionic states are anty-simmetrical to the application of the trasformation of exchange of identical particles.

$$\Psi(x_1, x_2) = -\Psi(x_2, x_1)$$




Assuming both electrons independent each other, the wave function of the state describing the two electrons can be written as the product of two one-electron functions (orbitals):

$$\Psi(x_1, x_2) = \psi_a(x_1) \cdot \psi_b(x_2)$$

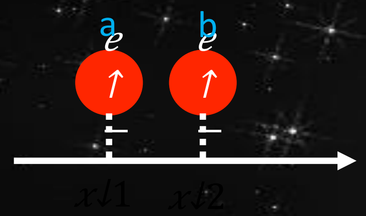



where $a, b$ are the quantum states of the electrons and $x_1, x_2$ their positions

# The Pauli Exclusion Principle (PEP)

Considering the following two properties of the fermions:

- Both electrons are indistinguishable: each electron is as likely to be as in A as in B




- The overall wave function is anti-symmetric respect to the exchange of particles

The complete wave function of the system should be written as:

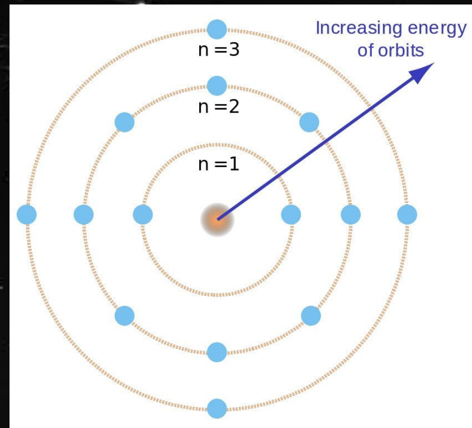
$$\Psi(x_1, x_2) = \psi_a(x_1) \cdot \psi_b(x_2) - \psi_b(x_1) \cdot \psi_a(x_2)$$

If the two electrons were in the same quantum states (*a*=*b*), $\Psi(x_1, x_2) = 0$

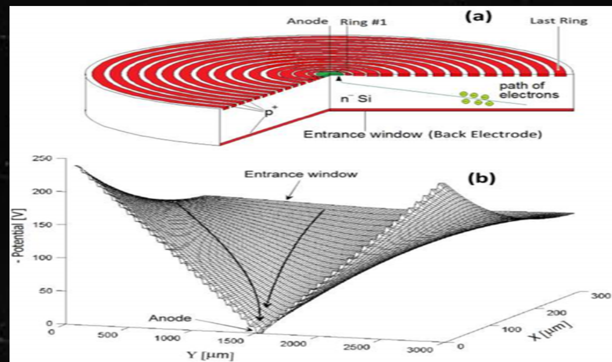
**The wave function vanishes : *no such state exists!***

# The Pauli Exclusion Principle (PEP)

The quantum state of an electron in an atomic orbital is described by 4 quantum numbers:




- The principal quantum number *n*: the distance between electron and nucleus (atomic shells)
- The orbital angular momentum *l*: determines the shape of an orbital, and the angular distribution. $l=0,1,\ldots,n-1$
- The magnetic quantum number *m*: determines the number of orbitals and their orientation within a subshell (splits orbitals). $m=-l,\ldots,0,\ldots,l$
- The spin quantum number $s=\pm 1/2$




$\{ e_1 (n=1, l=0, m=0, s=+1/2) e_1$

**EXAMPLE:** Orbitale 1s (n=1) ⟶

# The Nobel Lecture of Pauli

*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*

# How it is possible to investigate the PEP with VIP2

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.**

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.

# 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.

Asmall 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.

# 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

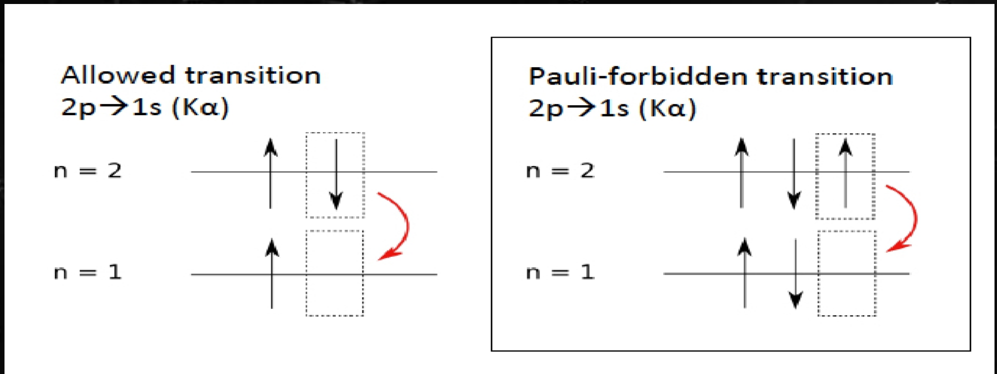
*C. Curceanu, L. De Paolis et.al., "Evaluation of the X-ray transition energy for the Pauli-principle-violating atomic transitions in several elements by using Dirac-Fock method", 2013, INFN-13-21/LNF.*

**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, ......

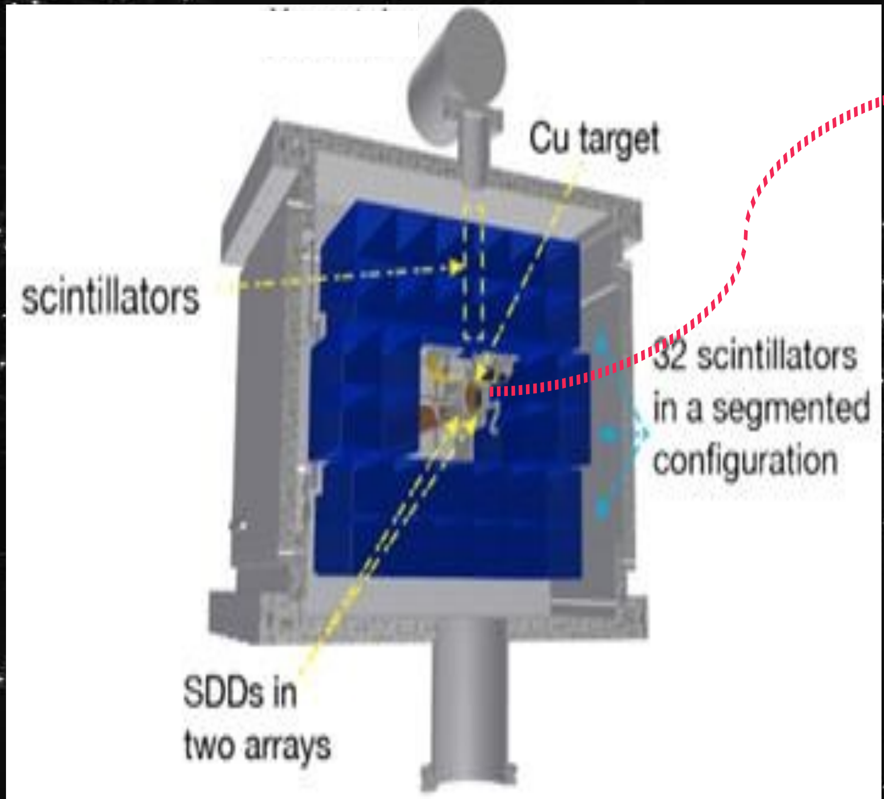



An e- in any level n>2 make a transition to level 2P.

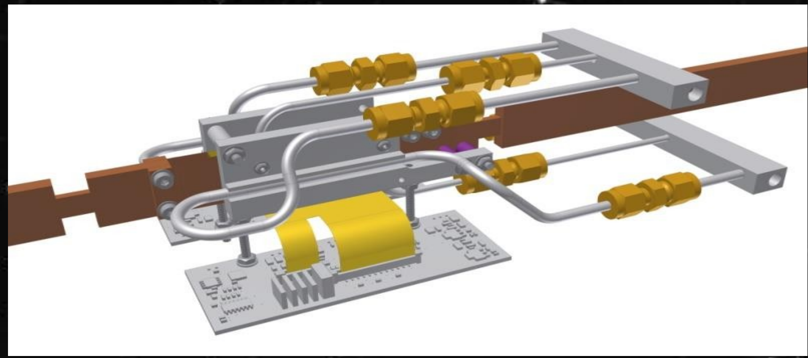
The non-Paulian transition to level 1S produces the emission of a PEP violating X-ray.

# The VIP2 experiment: purpose and apparatus.

Schematization of the VIP2 chamber



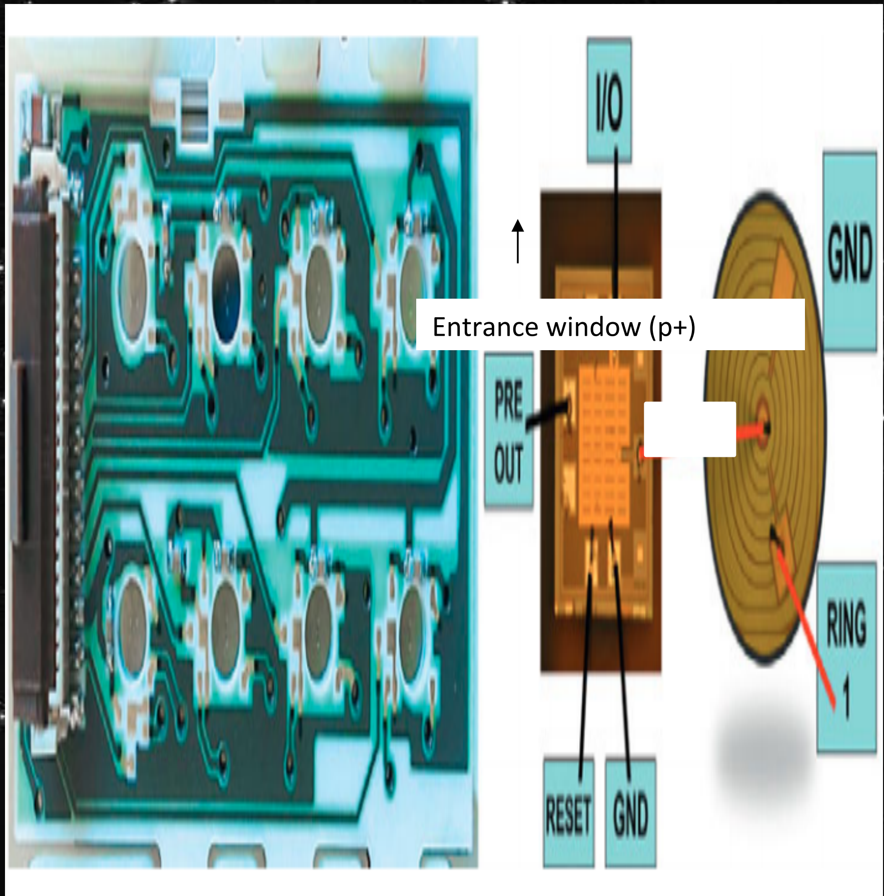

Target of VIP2

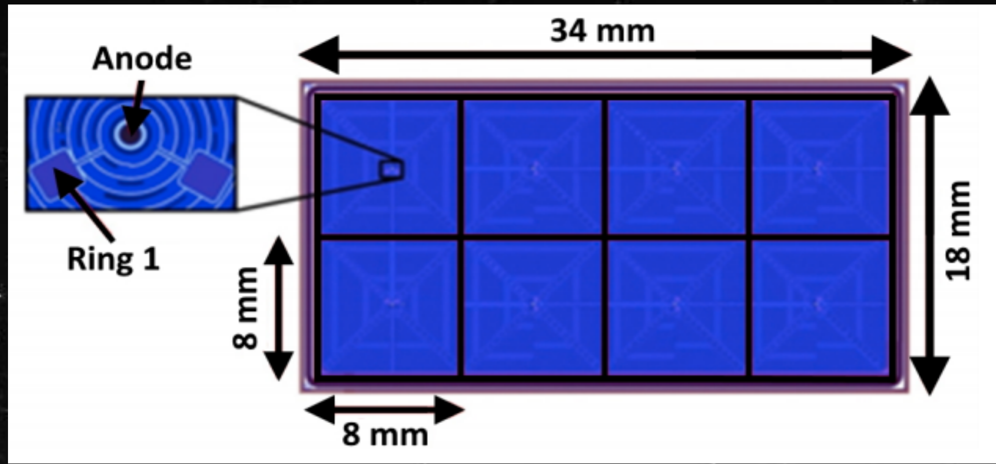


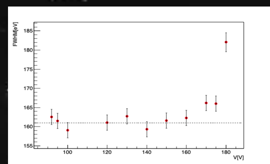
**Characteristics of the target:** the 2 strips (10 cm x 1 cm x 50 μm) are connected to an external generator by 2 thin copper bars. A current > 100 A is circulated on the copper strips. A water circuit cools them so that the temperature of the detectors does not increase by more than 2K.

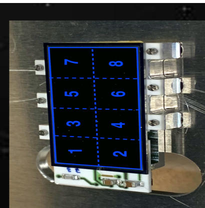
# The VIP2 experiment: Silicon Drift Detectors(SDDs)

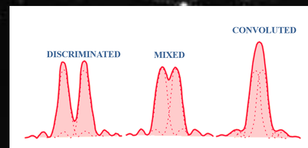
SDD CELL CROSS SECTION



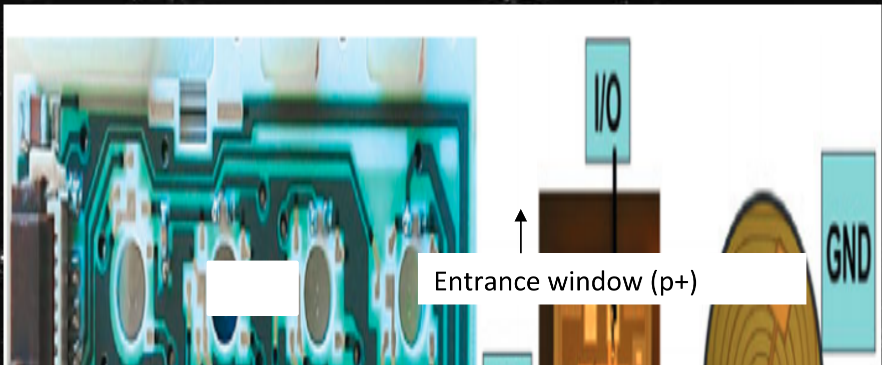


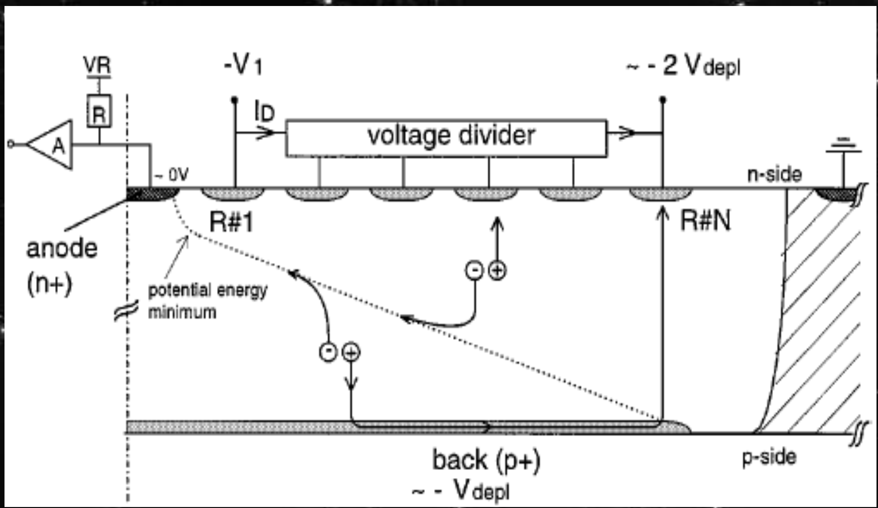


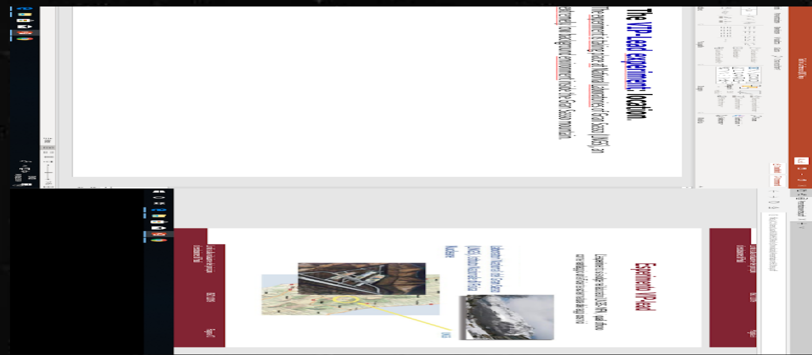

Each array consists of 8 SDD cells with 0.64 $cm^2$ of active area and 450 μm thickness each, which ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV

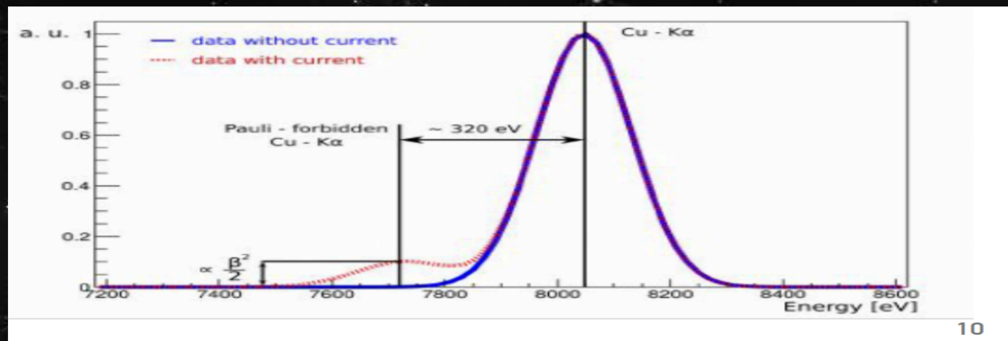
# The VIP2 experiment: Silicon Drift Detectors(SDDs)

SDD CELL CROSS SECTION






The VIP-2 experiment equips 4 SDD arrays, for a total of 32 SDD cell detectors.
Each SDD array has a total active area of 5.12 $cm^2$

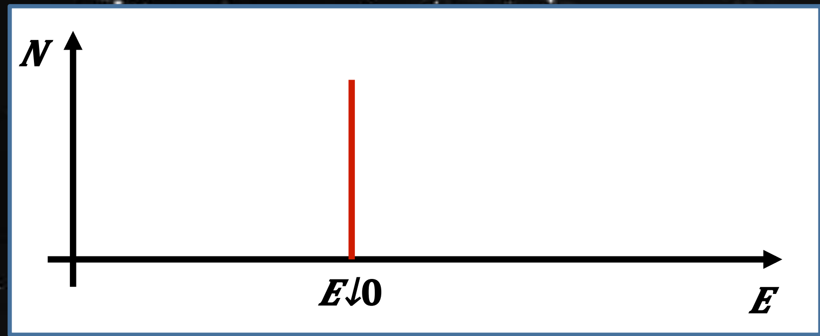
# The VIP2 experiment: Silicon Drift Detectors(SDDs)

## RESPONSE OF A DETECTOR

When a monocromatic beam (energy $E_0$) engraves on a detector:

- **IDEAL CASE: δ di Dirac**

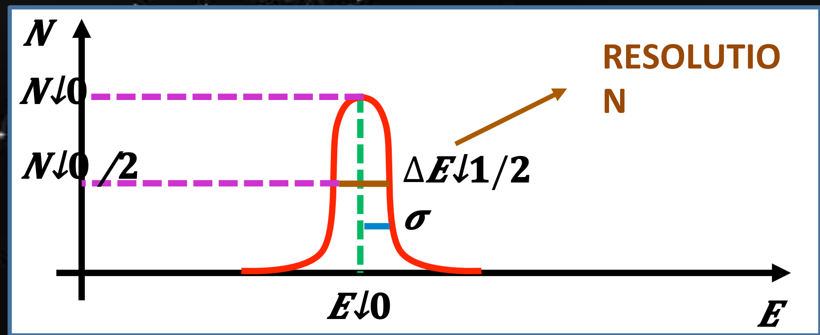
$$\delta(E-E_0)=\begin{cases}\infty, & E=E_0\\ 0, & E\neq E_0\end{cases}$$




- **REAL CASE: Gaussian centered in** $E_0$

  Due to fluctuations in the number of ionizations and deposited energy

$$G(E)=\frac{A}{\sigma\sqrt{2\pi}}\,e^{-\frac{(E-E_0)^2}{2\sigma^2}}$$



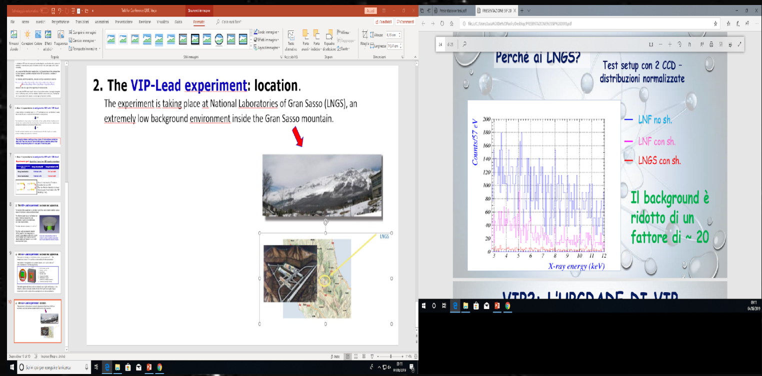
# The VIP2 experiment: Silicon Drift Detectors(SDDs)

The resolution is the detector capacity of discriminate close energies.

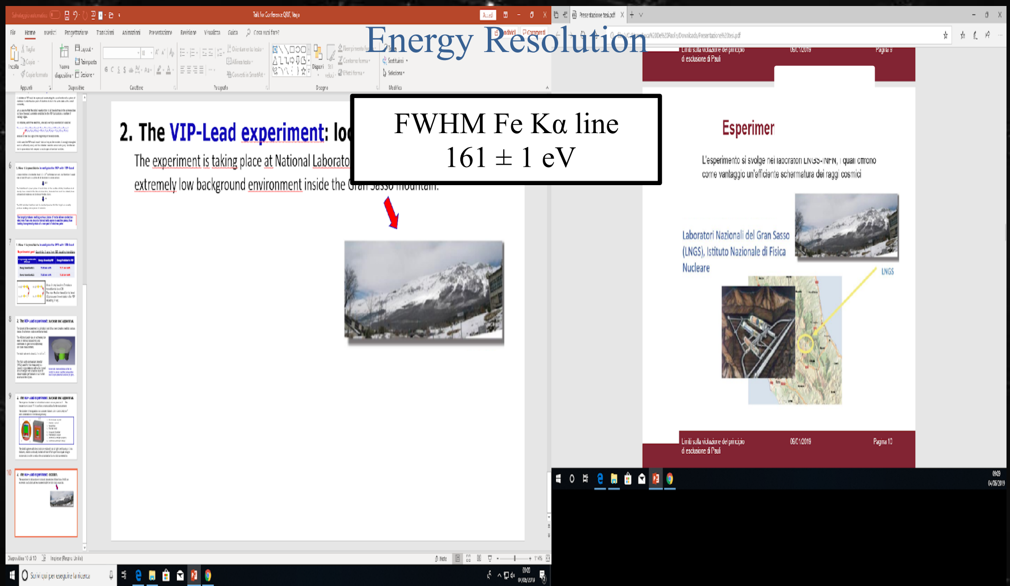
**Energy transition Kα allowed:** 8.05 keV in Cu

**PEP forbidden Kα energy:** ~ 7.74 keV in Cu

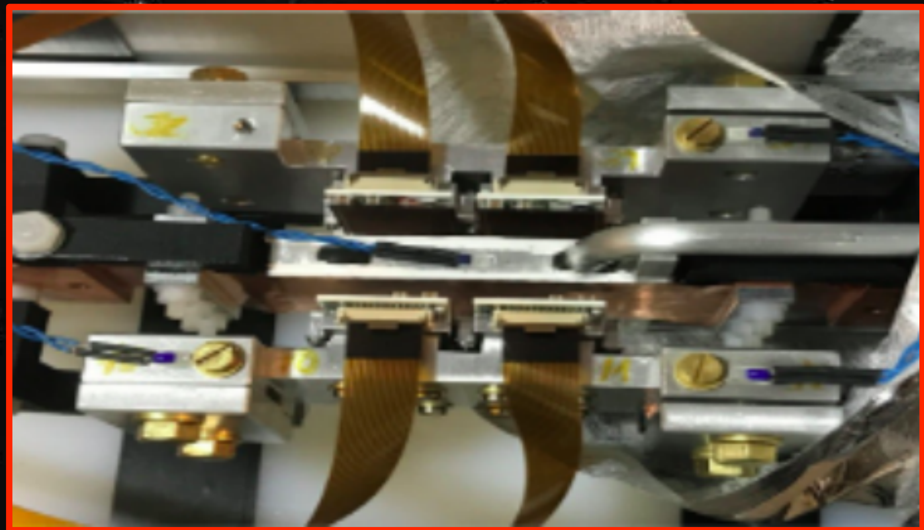
$\Delta E \approx 320\ eV$




Energy Resolution




FWHM Fe Kα line
161 ± 1 eV

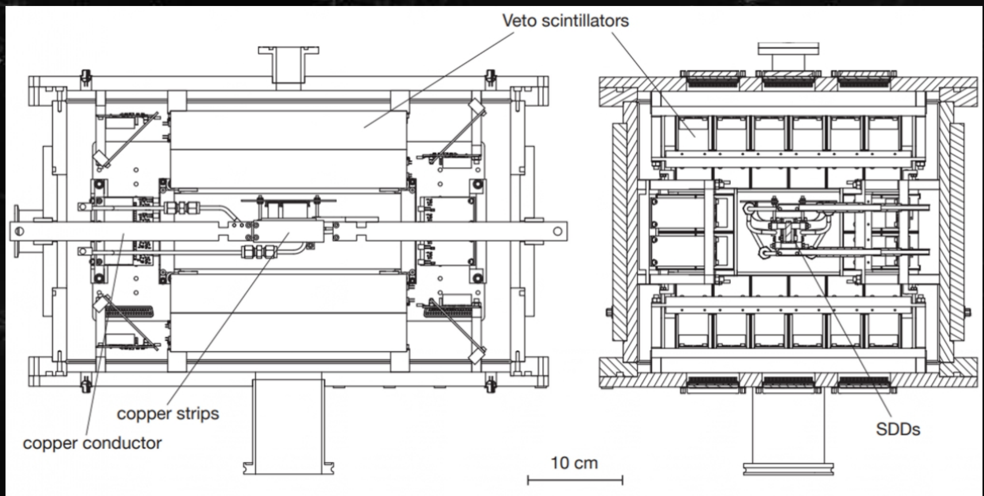


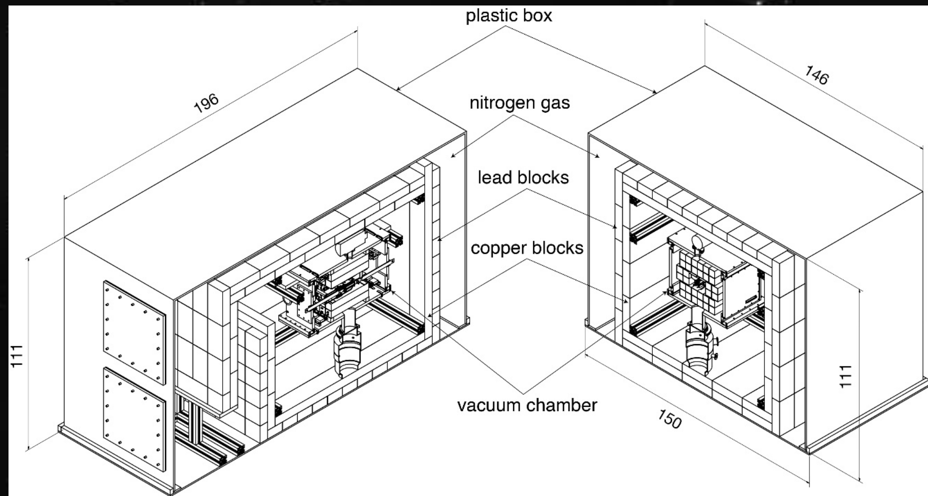
# The VIP2 experiment: Silicon Drift Detectors(SDDs)

The VIP-2 target and the detectors are placed inside a vacuum chamber, kept at $\approx 10^{-9}\ mbar$ of pressure. The SDDs are cooled to $\approx 170\ K\ (\approx -100\ °C)$, providing the best performances in resolution and efficiency.

A passive shield was installed outside the vacuum chamber, consisting of an inner layer of copper bricks and an outer layer of lead bricks.

**The passive shield will kill most of the background due to environmental gamma radiation.**

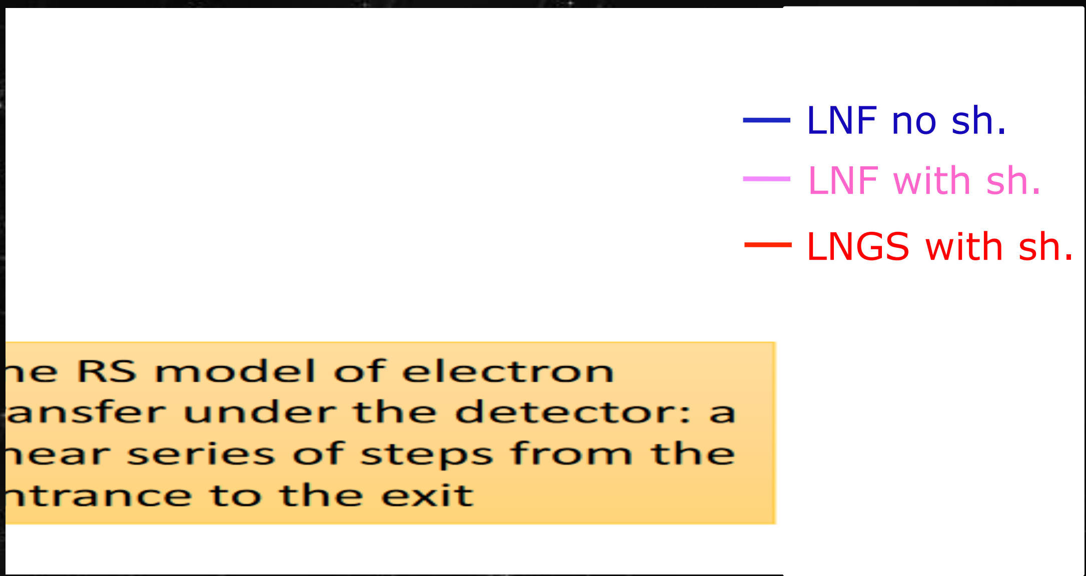


# The VIP2 experiment: Silicon Drift Detectors(SDDs)

The experiment is taking place at National Laboratories of Gran Sasso (LNGS), an extremely low background environment inside the Gran Sasso mountain.

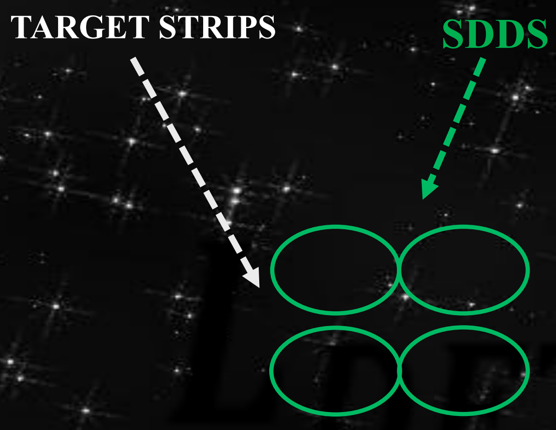
Graphic result of a test done with 2 CCD and normalized distribution

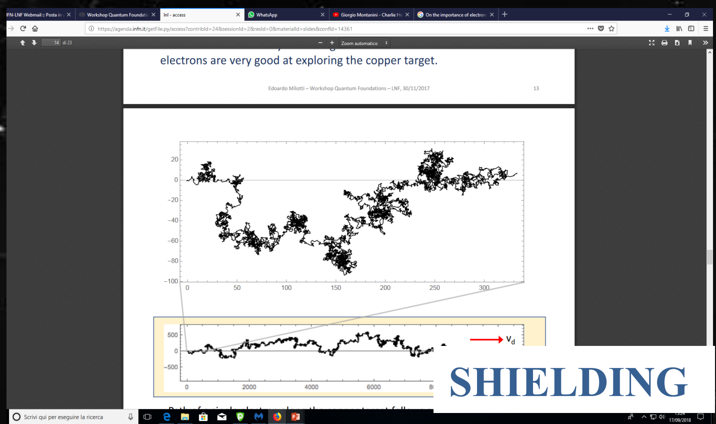




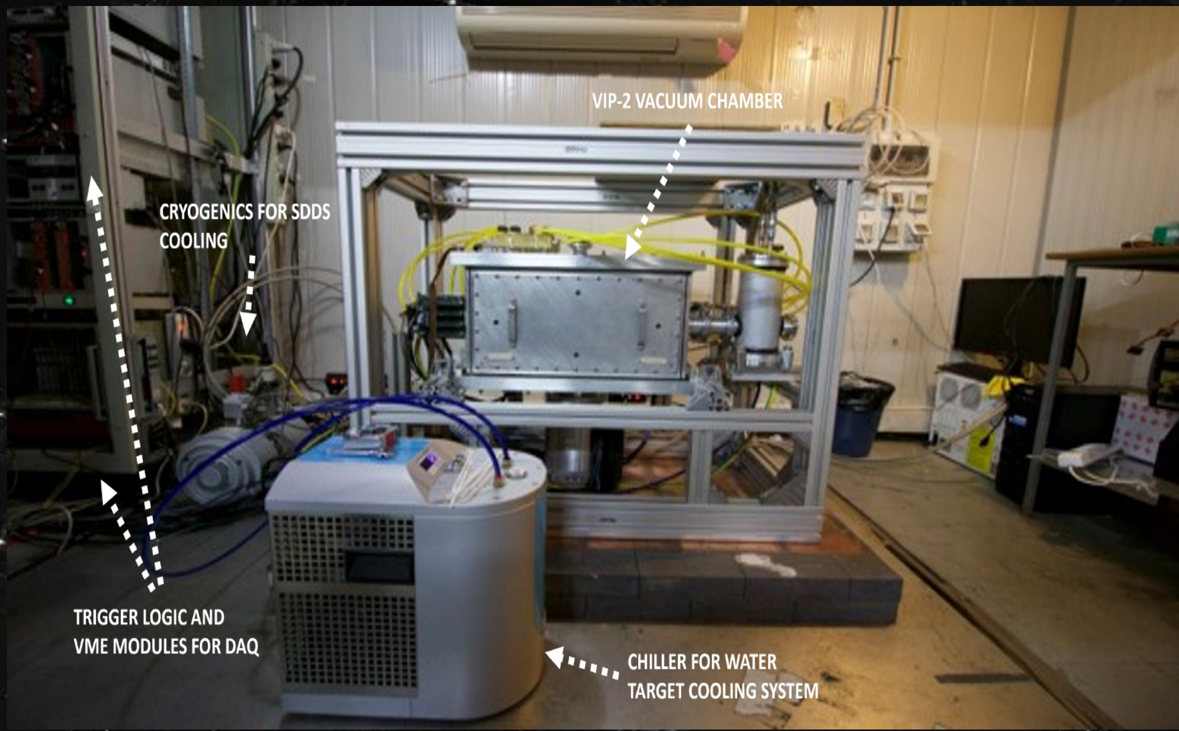
**The background is reducted by a factor ≈ 20**

# The VIP2 experiment: photo of the apparatus




SHIELDING



# The VIP2 experiment: Results and perspectives

An analysis was performed on approximately six months of data took by the VIP-2 experiment during December 2019–May 2020, with a current of 180 A circulating in the target for 83 days.

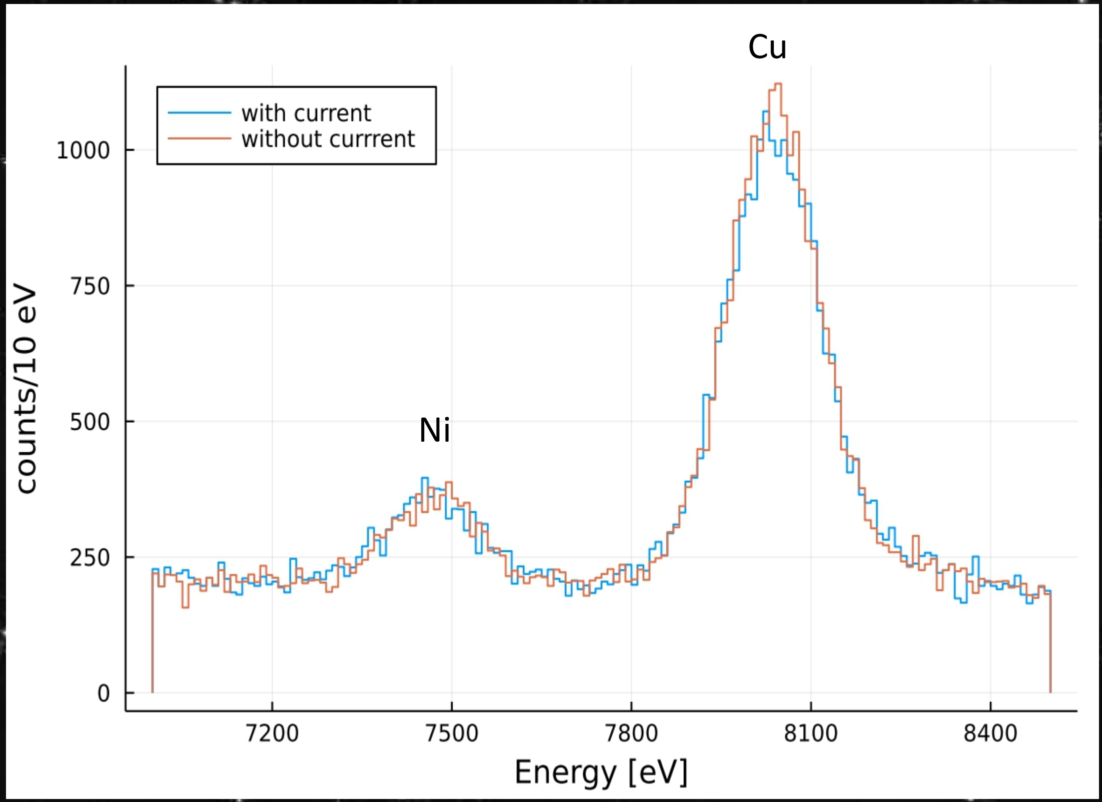
NO signs of violation was found

An upper limit on the probability of the violation of PEP for electrons in copper atoms was determined:

$$\boxed{\beta^2/2 \leq 8{,}6\times 10^{-31}}$$

**BEST RESULT FOR ELECTRONS IN COPPER ATOM**

VIP-2 is ACTUALLY in data taking



# Calculation of the limit

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

The factor of detection efficiency has been calculated using a simulation in GEANT4 and it is about 4%

Number of possible violating events extrapolated by the difference among the spectra

**BAYESIAN MODEL**

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

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

The lenght of the electronic path in copper is ≈7.5 cm

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

The capture probability of the electron by a copper atom is more than 1/10 respect to the scattering probability.

$$\beta^2/2 \leq 8.6 \times 10^{-31}$$

Confidence level 99.7%

# The «Random Walk» model

In the experiment VIP the number of scatterings for the single electron was calculated as:

$L_T/\mu$

- $L_T$ → Linear length of the target
- $\mu$ → Average free electron path

In VIP2 the target length is 10 cm (≈7.5 cm actually crossed by current) and the free electron average path in copper is 40 nm. The number of scatterings of the single electron for RS is $\approx 2\times10^{6}$

# The «Random Walk» model

The drift velocity of the electron in the copper is:

$v_d = I/newz \sim 5\ mm/s$

*n is the density of electrons at m ^ 3, and is the elementary charge, w and z are the width and thickness of the target*

The mean time of crossing the target for the single electron is **Δt=<u>16 seconds</u>**

Average time between two collisions is: $\tau = 2,5 \times 10^{-14}\ s$

The number of scatterings of the single electron can be calculated as:

$\Delta t/\tau = 6,4 \times 10^{14}\ scatterings \gg 2 \times 10^{6}$

Following the «Random walk» model the upper limit set by VIP-2 could be brought to a value of:

$$\boxed{\beta^2/2 \leq 6,8 \times 10^{-43}}$$

# WHY INVESTIGATE PEP?

The Pauli Exclusion Principle is a fundamental cornestore of the quantum physics.

Even a small violation of PEP could have important effects in various fields of physics and science and explain numerous phenomena.

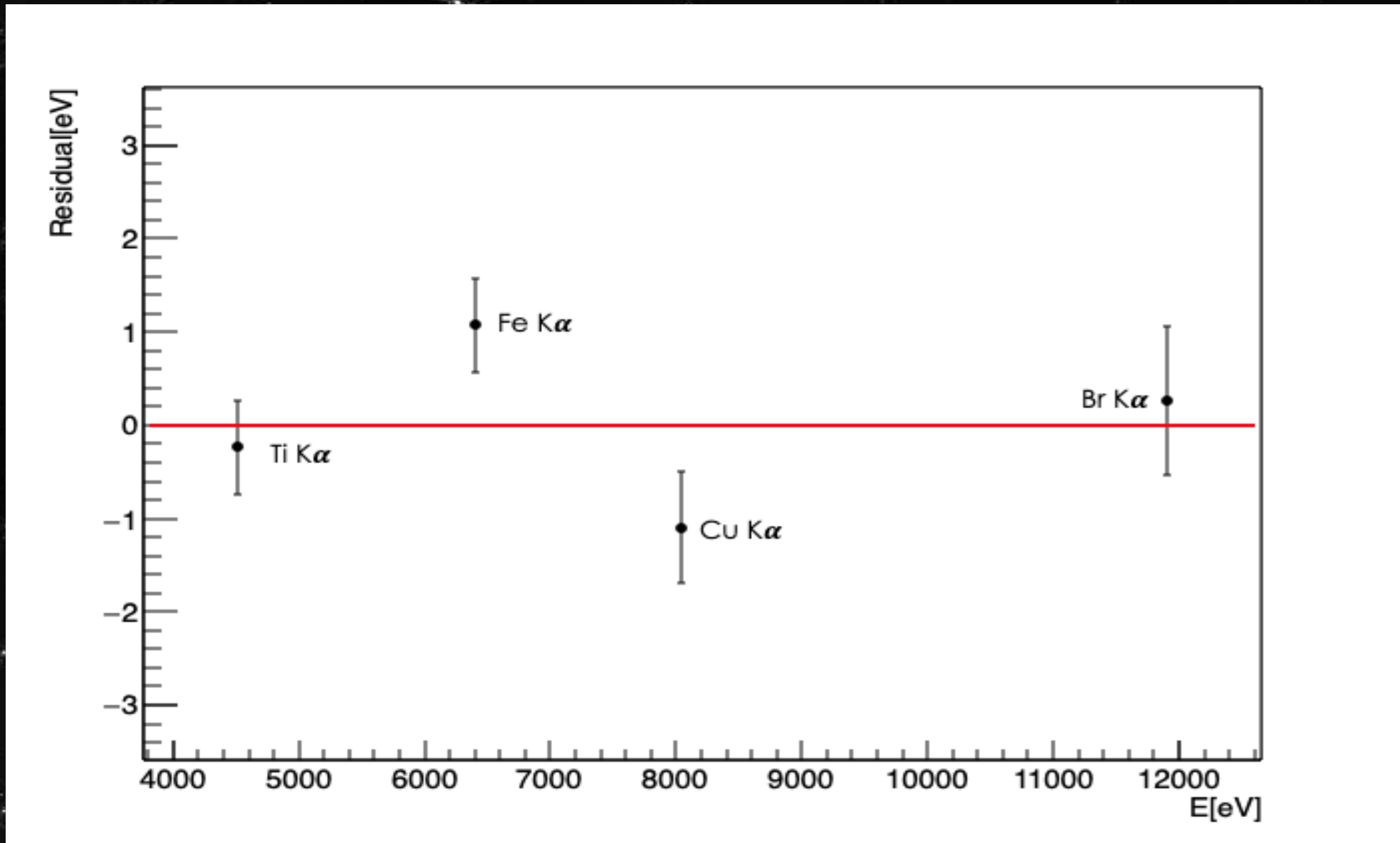
The number of electrons in the observable universe is $\approx 10^{80}$ (Number of Eddington).

**We tested only a very small fraction of the electrons in the universe!**

A violation of the PEP could be induced by the space-time non-commutativity, as predicted by several models in **Quantum gravity**, above the Planck Scale $(10^{19}\ GeV)$.

**Testing the PEP we provide fundamental constraints for these models and test their validity**

# WHY INVESTIGATE PEP?



# CONCLUSION

**VIP2: MAY THE FORCE BE WITH YOU**


W.E. PAULI

Thank you all for your attention !!

# 4. NEW upper LIMIT for the PEP violation probability

Subtracting the spectra got with data taking until July 2017:

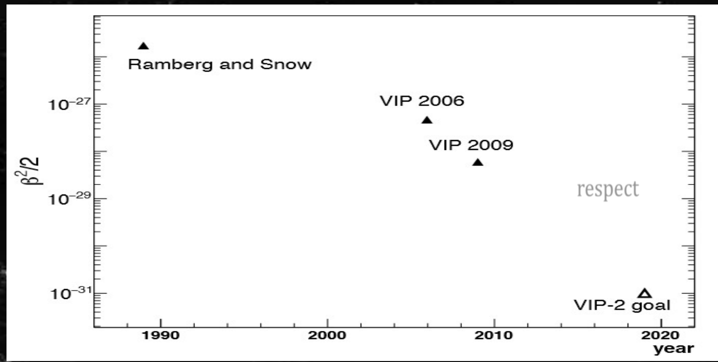
$\Delta N_x = 97 \pm 91$ Normalized to 81 days

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

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.



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

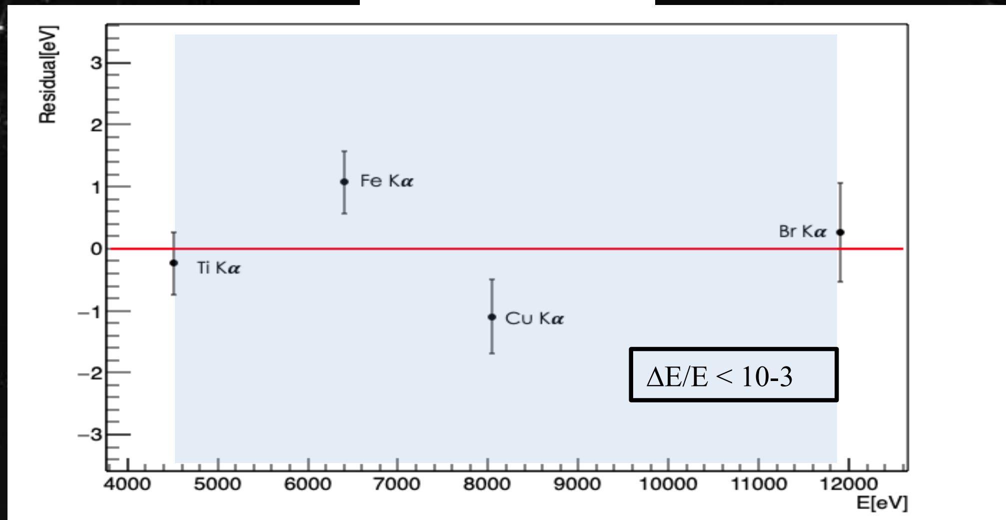
The linearity of the SDDs allows the use of the formula:

$$E[eV] = R[eV/ch] \cdot E[ch] + A[eV]$$

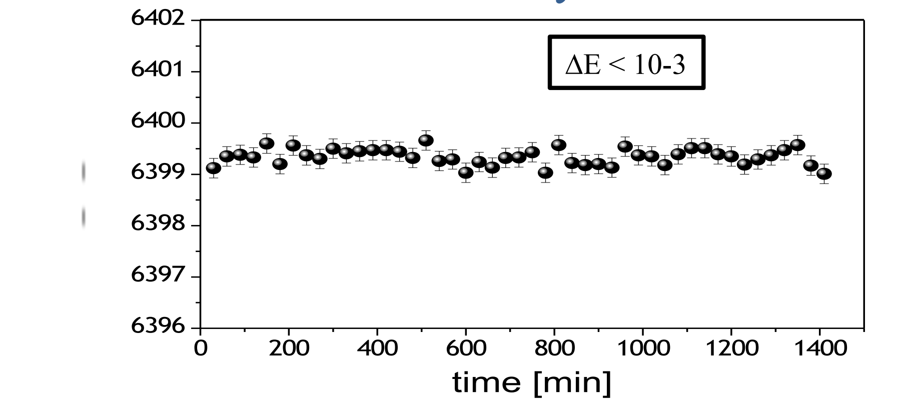
$R = \frac{E_{K\alpha}^{Fe}(ch) - E_{K\alpha}^{Ti}(ch)}{E_{K\alpha}^{Fe}(eV) - E_{K\alpha}^{Ti}(eV)}$ = calibration coefficient.

A is an Offset

Linearity




Stability




The stability of the detectors ensures its precision during the time.

M Miliucci *et al* 2021 *Meas. Sci. Technol.* **32** 095501

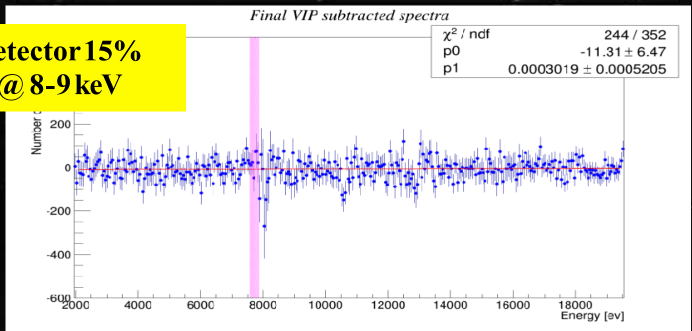
# 2. Historical Goals: Ramberg and Snow(RS) experiment

[Phys. Lett. B238 (1990) – 438]

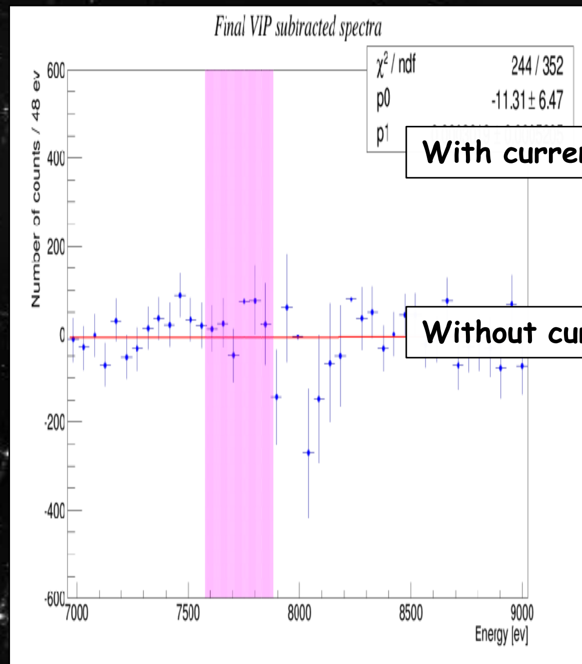
In 1988 Ramberg and Snow performed a dedicated experiment which sought to identify anomalous transition, forbidden by PEP, of electrons in a copper target crossed by a current.

**Schematization of the RS apparatus**

**gas-tube detector 15% resolution @ 8-9 keV**




**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:

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

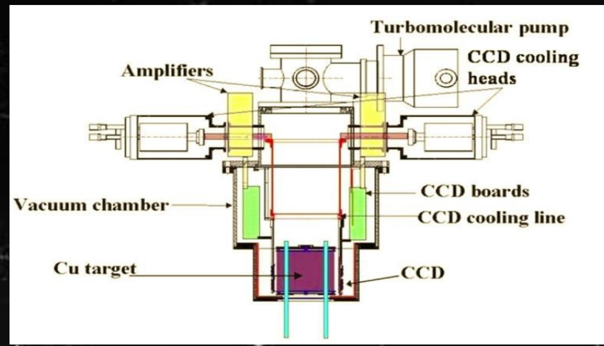
# INDEX

1. How it is possible to investigate the Pauli exclusion principle (PEP) with VIP2
2. Historical goals: from Ramberg and Snow(RS) experiment to VIP
3. The VIP2 experiment: purpose and apparatus
4. The calculation of a NEW upper LIMIT for the PEP violation probability of electrons in copper got with data acquired until July2017.

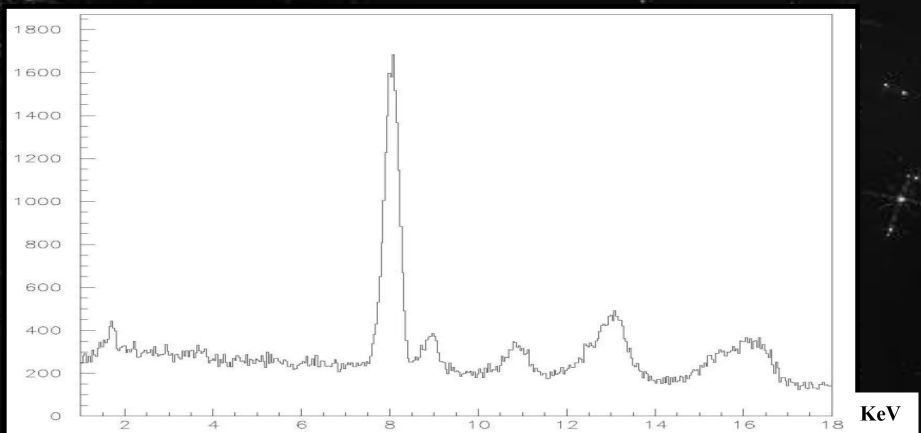
# 2. Historical Goals: The VIP experiment

Improvements made respect to RS experiment:

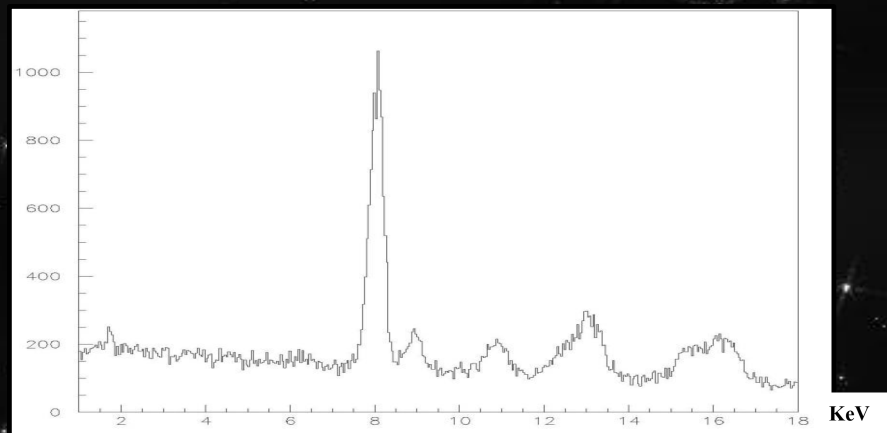
- More sensitive X-ray detectors covering more surface: Charge Coupled Device (CCD)
- A cleaner and low-background experimental area (LNGS)
- A better statistic due to the longer time taken.




**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]*

$N_X + \varepsilon_X = 37 \pm 146$

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

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…

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

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

# 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 )**

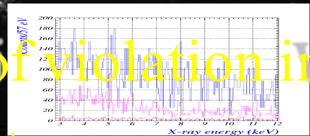
**attraverso le relazioni:**

$$a^{+}|0\rangle = |1\rangle \qquad a|0\rangle = 0$$

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

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

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 β → 0 we find the Fermi – Dirac statistic and the exclusion principle is absolutely valid.**

# Why at LNGS? 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 ~ 20**

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

O. Greenberg, one of the pioneers of parastatistic studies, says that a possible violation of the PEP could be due to:

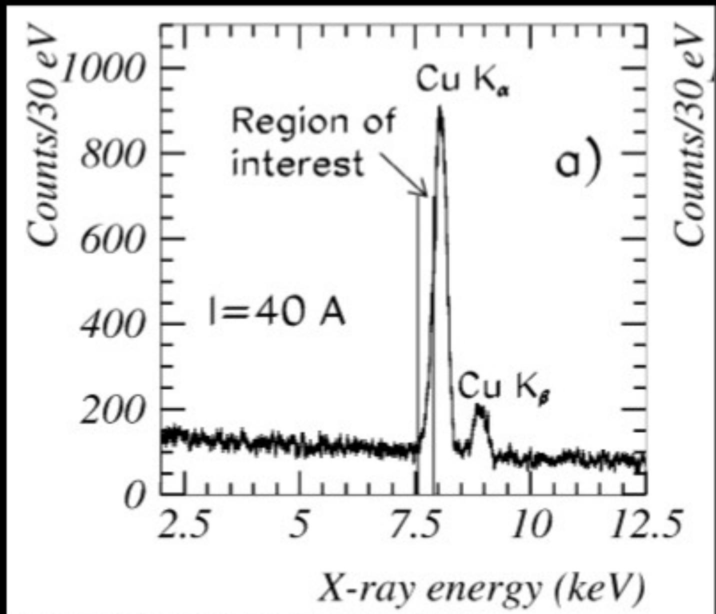
"Possible external motivations for violation of statistics include: (a) violation of CPT, (b) violation of locality, (c) violation of Lorentz invariance, (d) extra space dimensions, (e) discrete space and/or time and (f) noncommutative spacetime....".

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

# VIP2: l'upgrade di VIP

## From CCDto SDD – Energy resolution

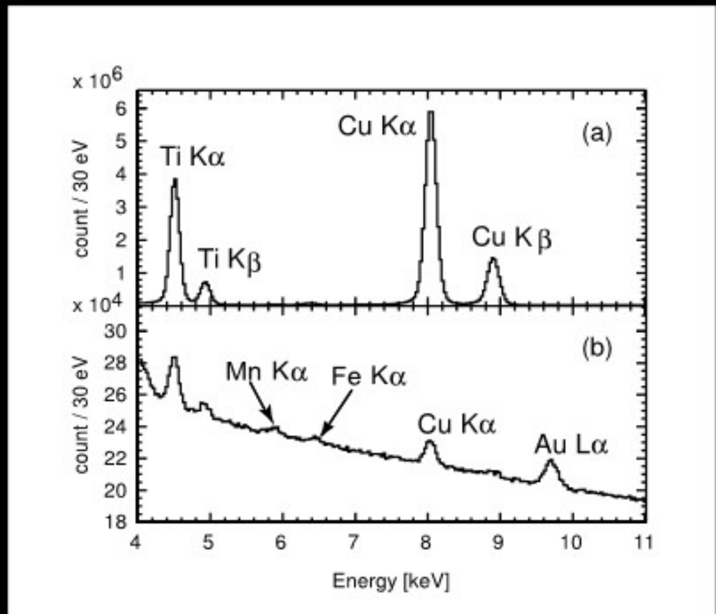
VIP




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

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

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

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 ($\approx$10 cm)

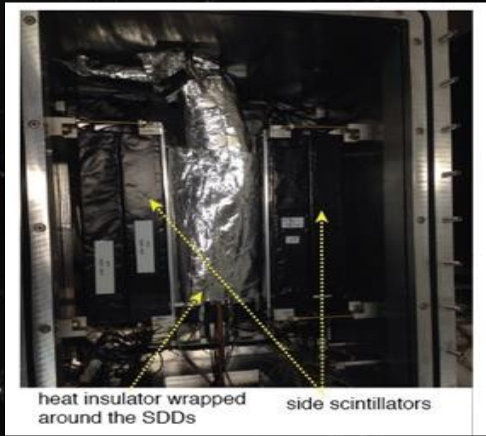
$\mu$ → Mean free path: $\mu = 3.9 \cdot 10^{-8} m$

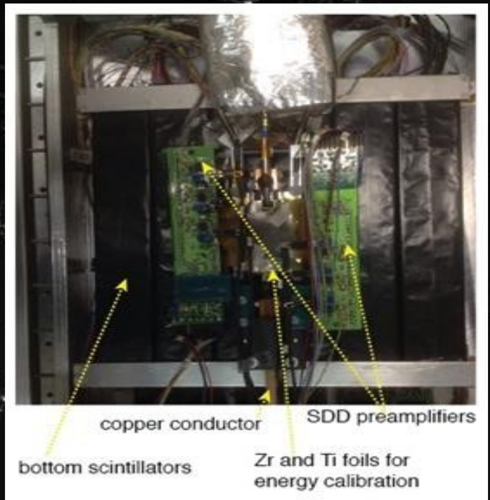
The probability of electron capture is greater than 1/10 of the scattering probability.

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

Confidence level: 99.7%

# 3. The VIP2 experiment: the VETOsystem




Used to select incident events with high energy RC unshielded from rock and environmental background.

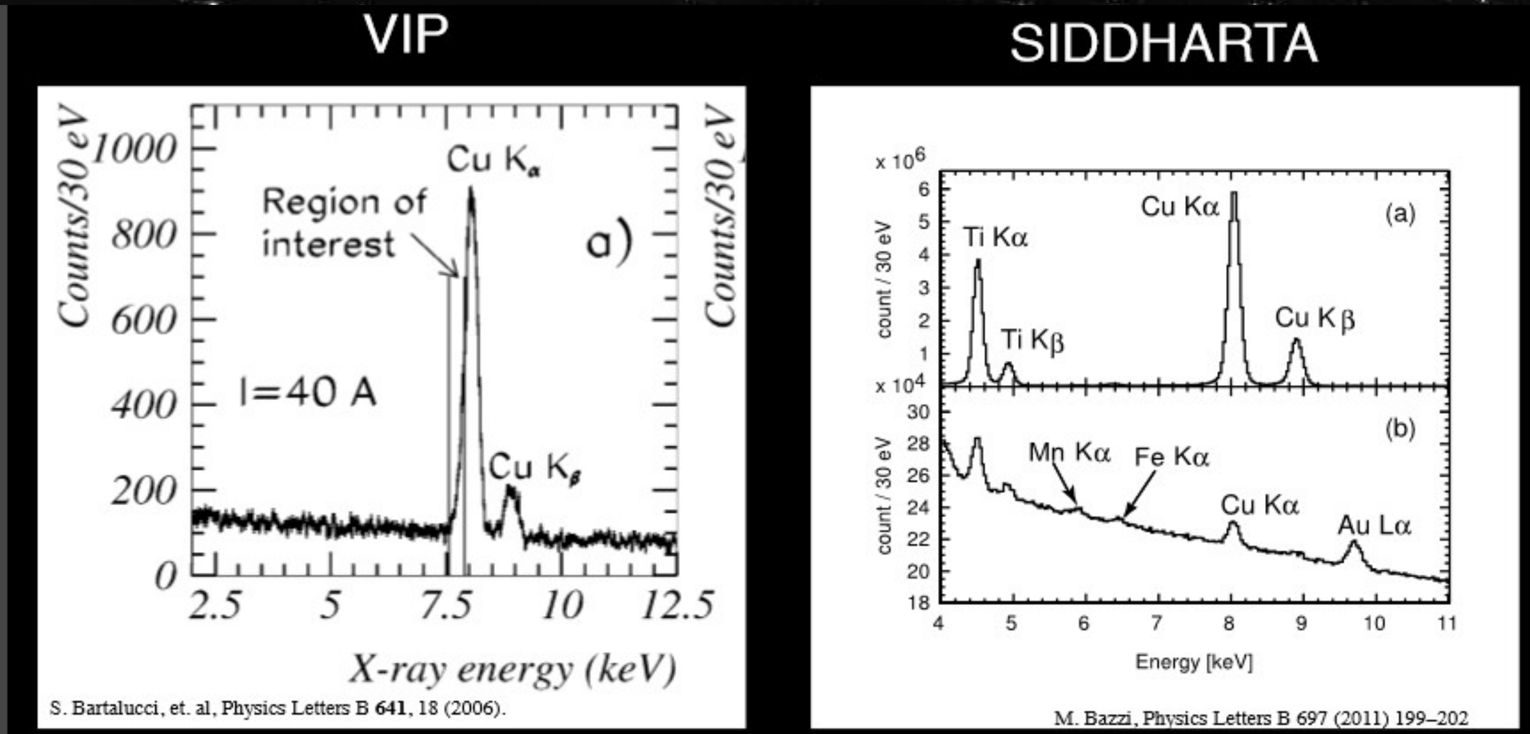
Composed of 32 plastic scintillators measuring 45x3x3 cm and covering a solid angle > 90% compared to the target.

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: Silicon Drift Detectors(SDDs)

## From CCDto SDD – Energy resolution



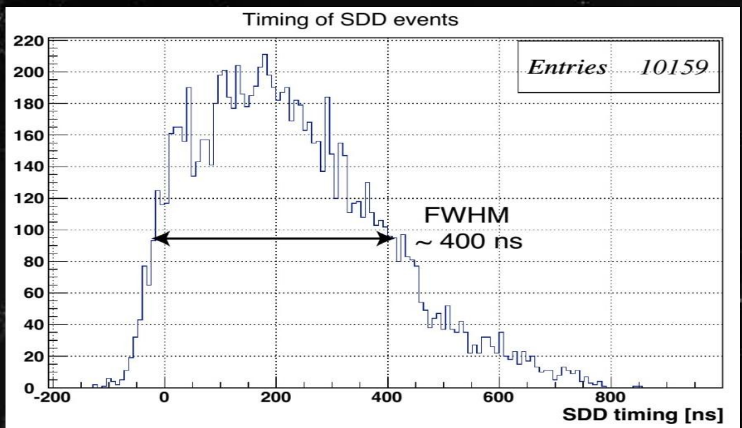

FWHM 340 eV
@ 8 keV

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 Kseries 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 EVEN TS

# 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 |

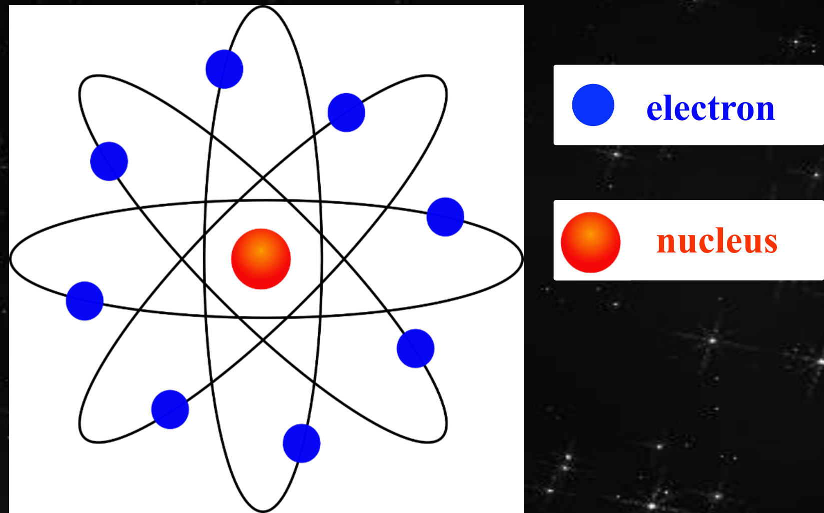
**FUTURE GOAL:**

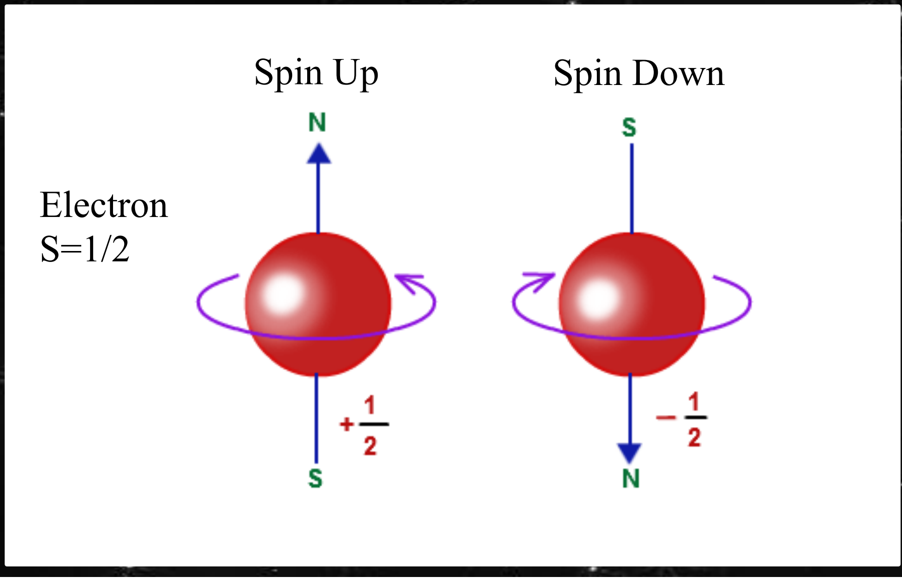
$$\boxed{\frac{\beta^2}{2} < 4.7 \times 10^{-29} \rightarrow 10^{-31}}$$

# The Pauli Exclusion Principle (PEP)

The Pauli Exclusion Principle (PEP) states that, in a quantum system, two fermions cannot occupy the same quantum state simultaneously.

Electrons are fermions: particles with half-odd-integer spins s (1/2, 3/2 ….)




The spin is the intrinsic angular momentum of a particle.

**Because of PEP, in an atomic system each atomic orbital cannot be occupied by more than two electrons having opposite spin.**

# The Pauli Exclusion Principle (PEP)

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 ofnature".

**Messiah A.M.L. and Greenberg O.W.; *Physics Review* 1964, 136, B248.**