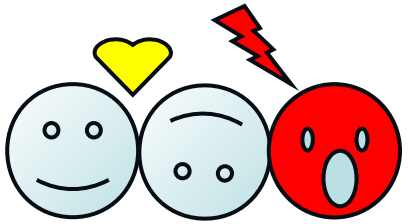
New experimental limit on the Pauli Exclusion principle violation by electrons (the VIP experiment)



Antonio Romero, LNF-INFN
On behalf of the VIP collaboration

LNF Spring School
Frascati, 11-15 May 2008

THE VIP COLLABORATION

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Pauli Exclusion Principle

“No two identical fermions may occupy the same quantum state simultaneosly”

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

VIP is an experiment to test the Pauli Exclusion Principle (PEP) for electrons in a clean environment (LNGS).

Goal of VIP

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

From:

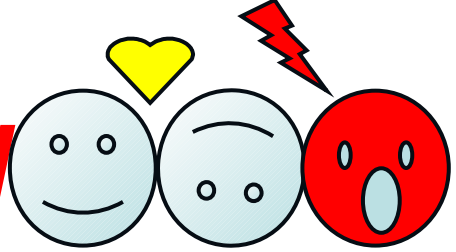
$$\beta^2/2 \leq 1.7 \cdot 10^{-26} \; (> 95 \; C.L.)$$

(Ramberg & Snow -1990)

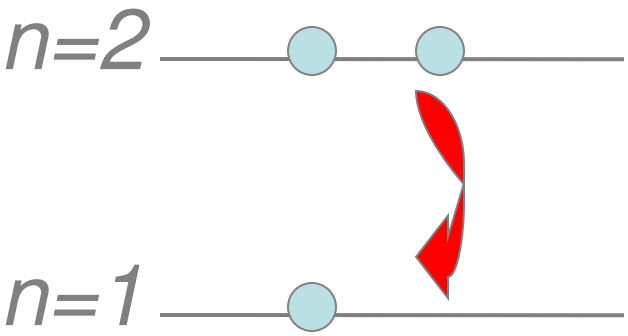
to

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

Experimental method

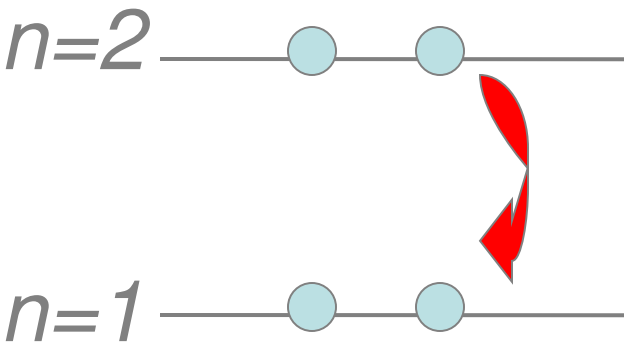


Search for anomalous X-ray transitions



Normal 2p →1s transition

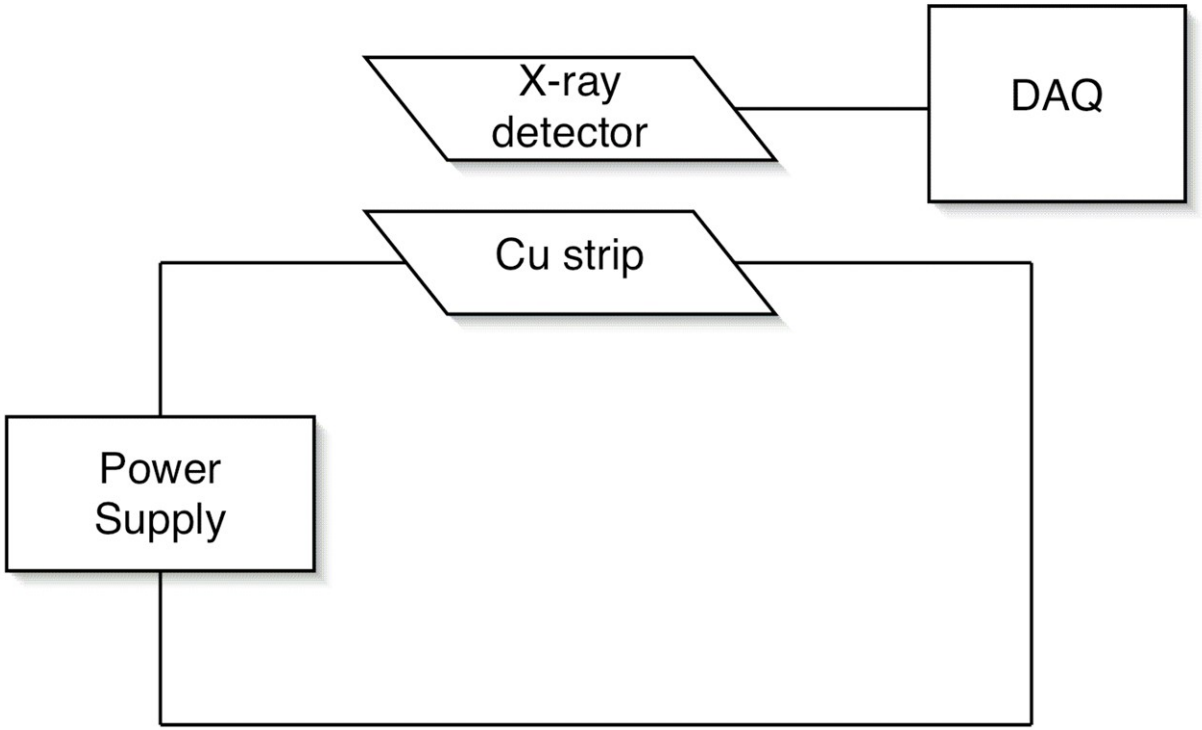
8.05 keV in Cu



2p →1s transition violating Pauli principle

~ 7.7 keV in Cu

The (previous) Ramberg & Snow experiment



(Experiment performed in the Muon building at Fermilab)

E. Ramberg and G. A. Snow, Phys. Lett. **B238** (1990) 438

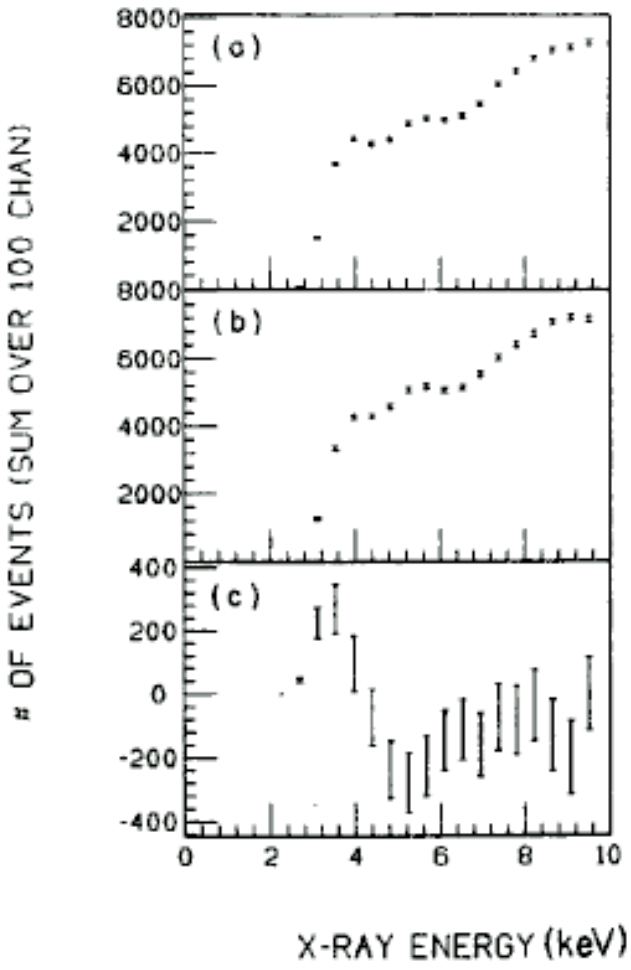


Fig. 2. (a) Number of triggers summed over 100 ADC channels, plotted versus equivalent X-ray energy with current-on in copper strip below X-ray counter. (Note the points are separated by 50 channels, so that only every other point is statistically independent). (b) Same as (a) but with no current passing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

Ramberg & Snow result

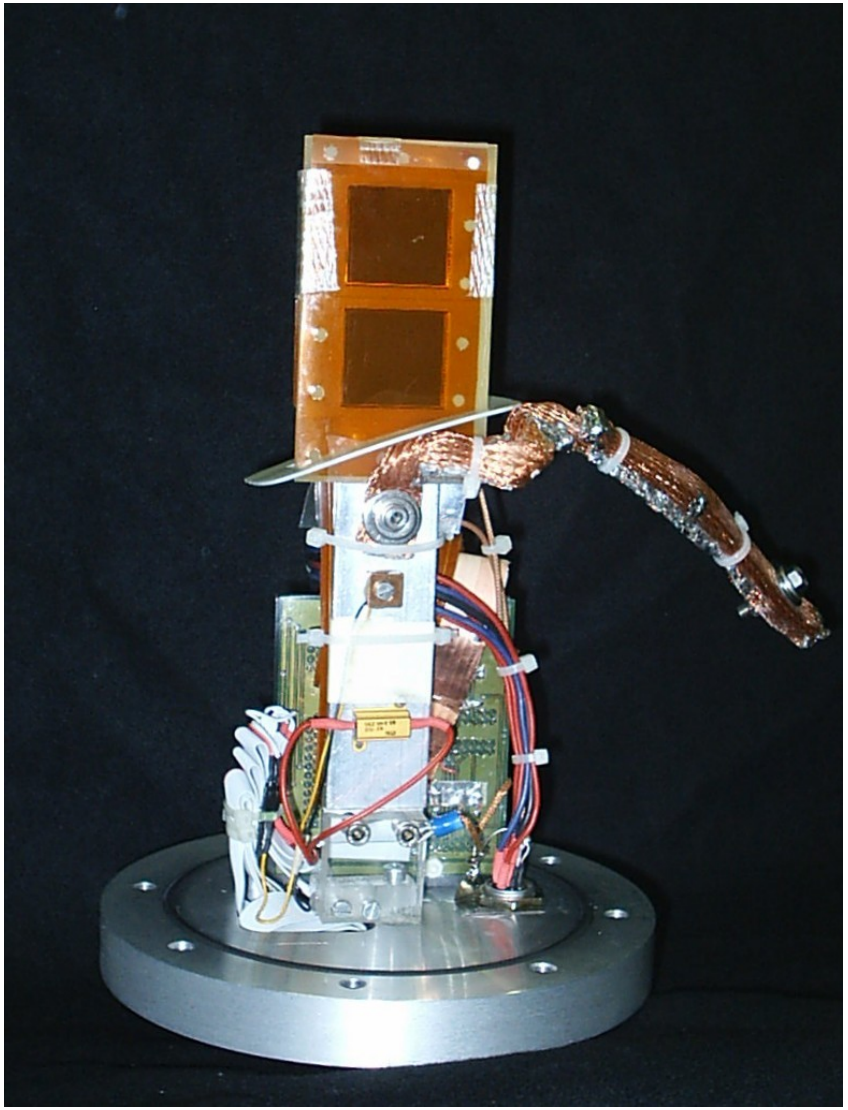
$$\beta^2/2 \leq 1.7 \cdot 10^{-26} \; (> 95\ C.L.)$$

The VIP experiment

VIP is a much improved version of the RS experiment:

3. sensitive, large-area, X-ray detectors
4. clean, low-background experimental area (LNGS)
5. Integrate much more current

2 CCD detectors

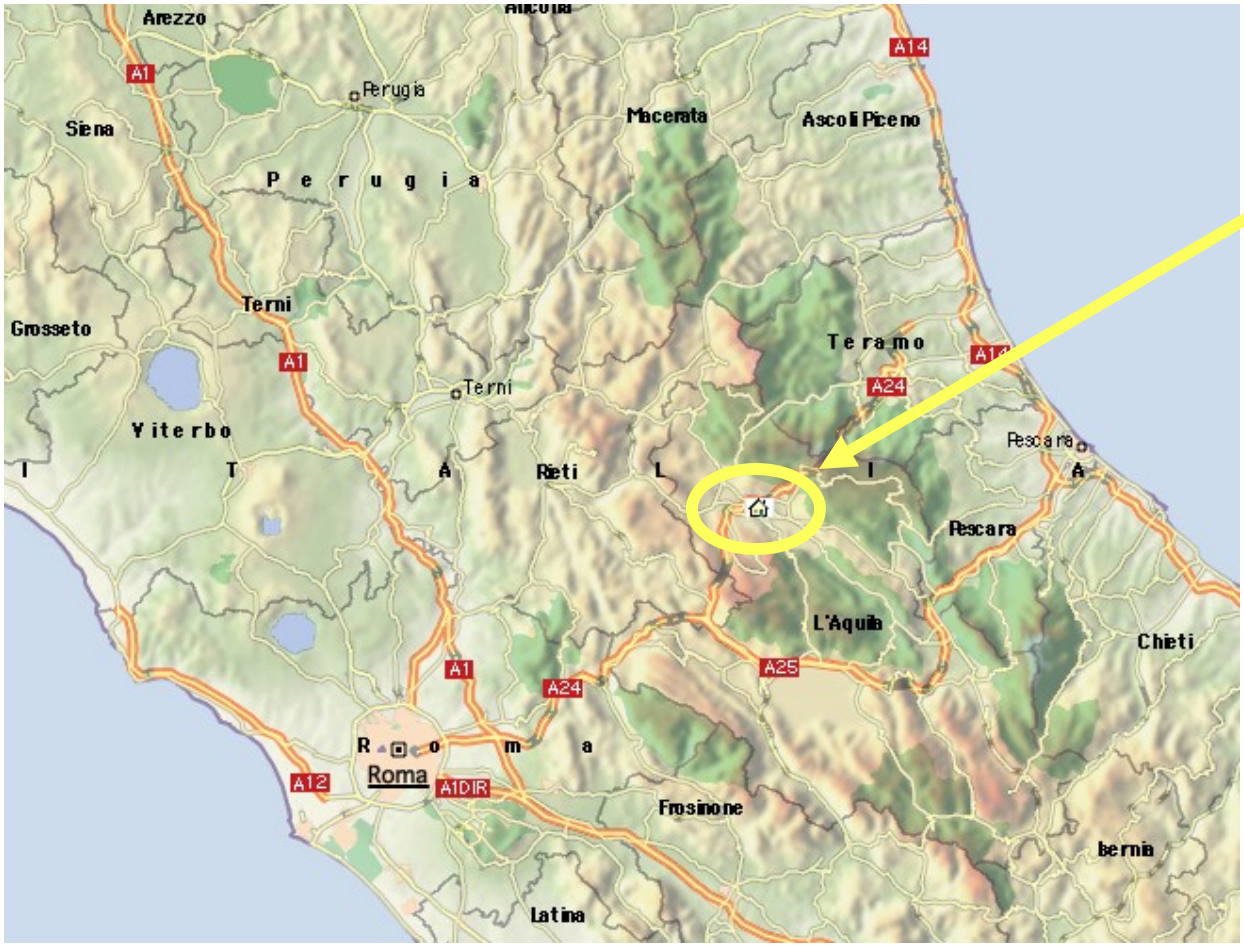


Experimental activities since October 2004 (approval)

- ***November-December 2004:*** ***measurements with a 2-CCD test setup in the laboratory, with and without shielding;***
- ***End of December 2004:*** ***transportation and installation of the test setup setup at LNGS and first tests***
- ***21 February 2005 – 28 March 2005:*** ***5 weeks of DAQ with shielding with the test setup at LNGS;***
- ***Spring-Autumn 2005****: built components of the VIP setup; tests and assembly of the VIP apparatus at LNF;*
- ***21 November – 13 December 2005:*** ***3 weeks of VIP DAQ at LNF;***
- ***Autumn 2005 – beginning 2006****: preparation of the experimental site at LNGS;*
- ***February 2006:*** ***transportation and installation of the definitive VIP setup at LNGS and first measurements without shielding;***
- ***April 2006:*** ***installation of the final shielding for the VIP setup and start DAQ for 2 years measurements, with and without current.***

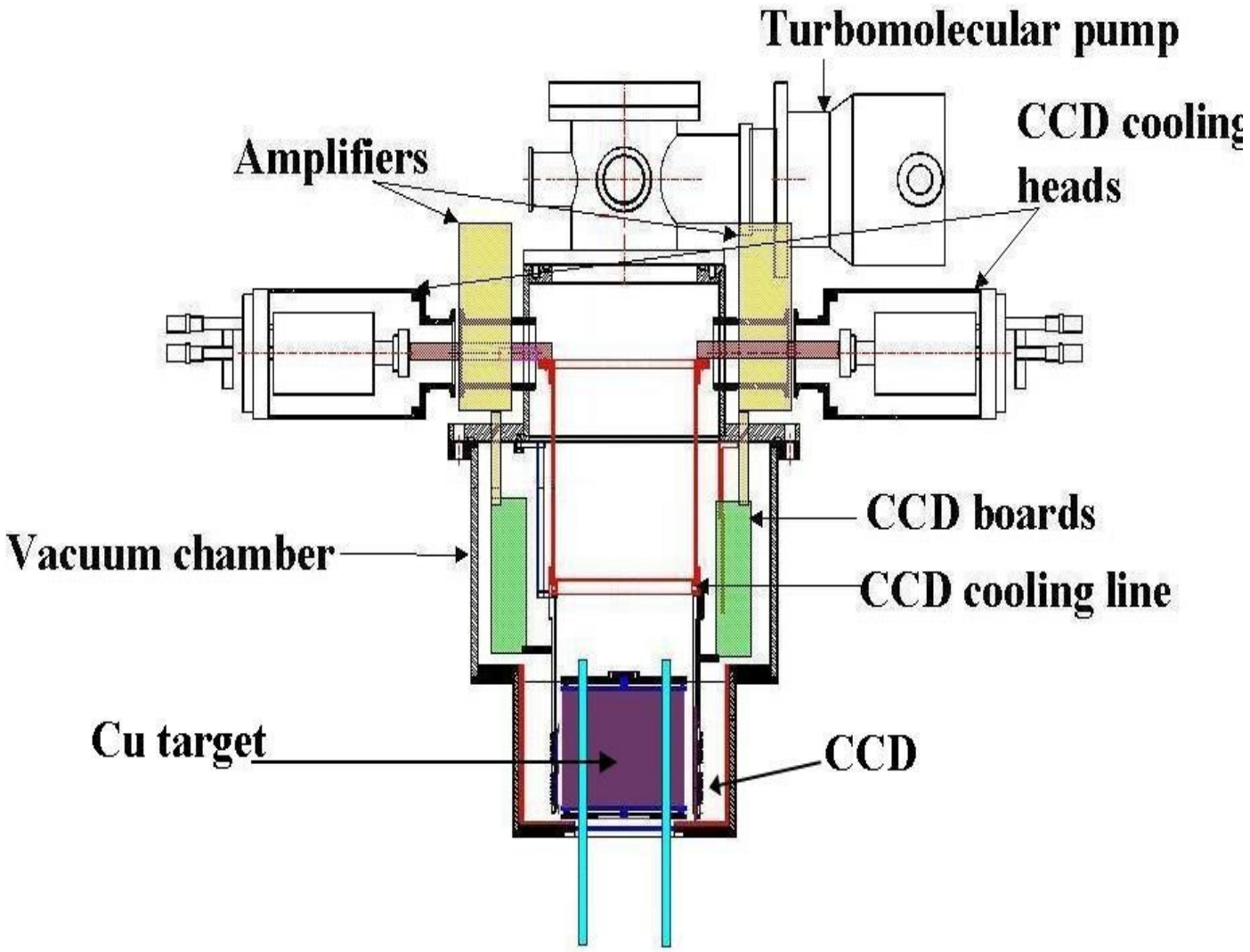
Test site and final location:

Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare



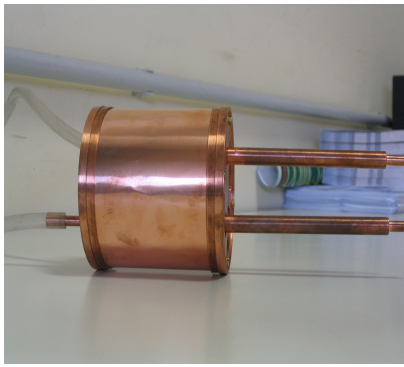
LNGS

The VIP setup

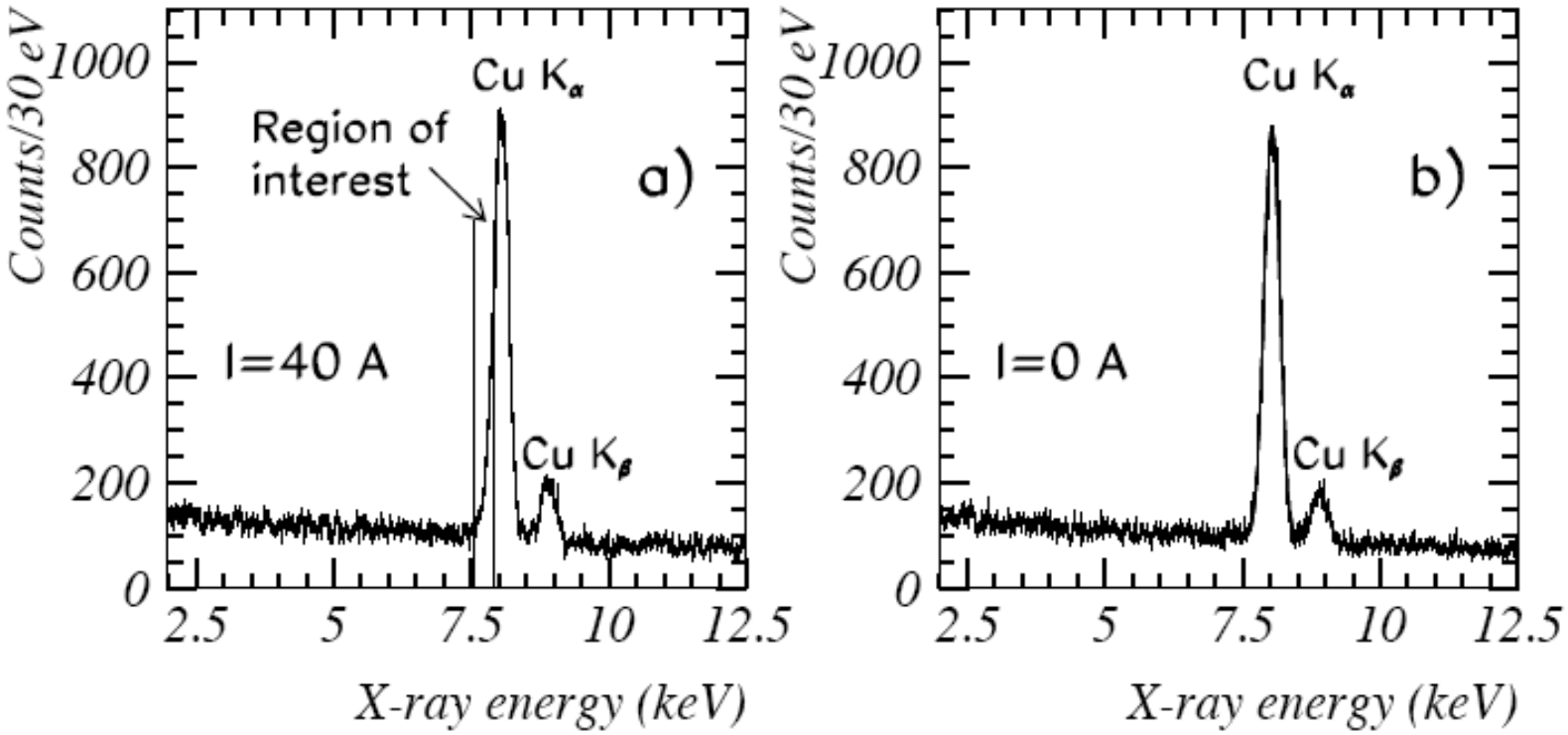


The VIP setup

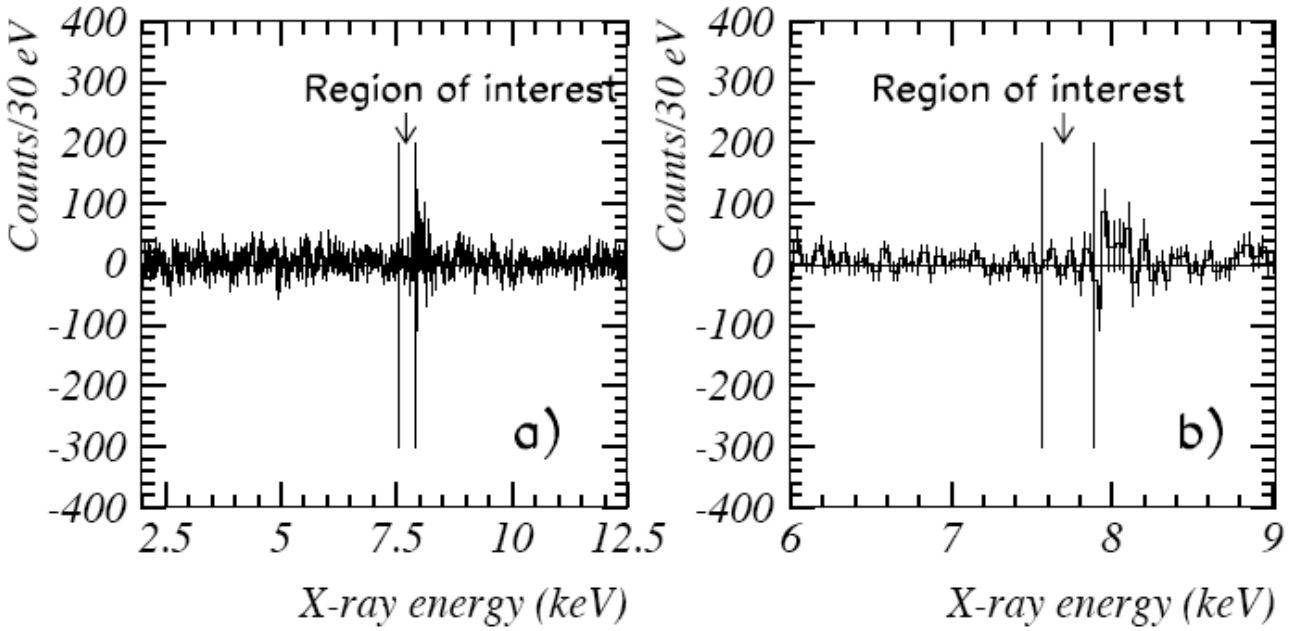
Cu Target



Final setup has been used for preliminary measurements at the LNF-Frascati laboratory – 21 nov. 2005 - 13 dec. 2005



subtracted spectra (“current” - “no current”)



First resu

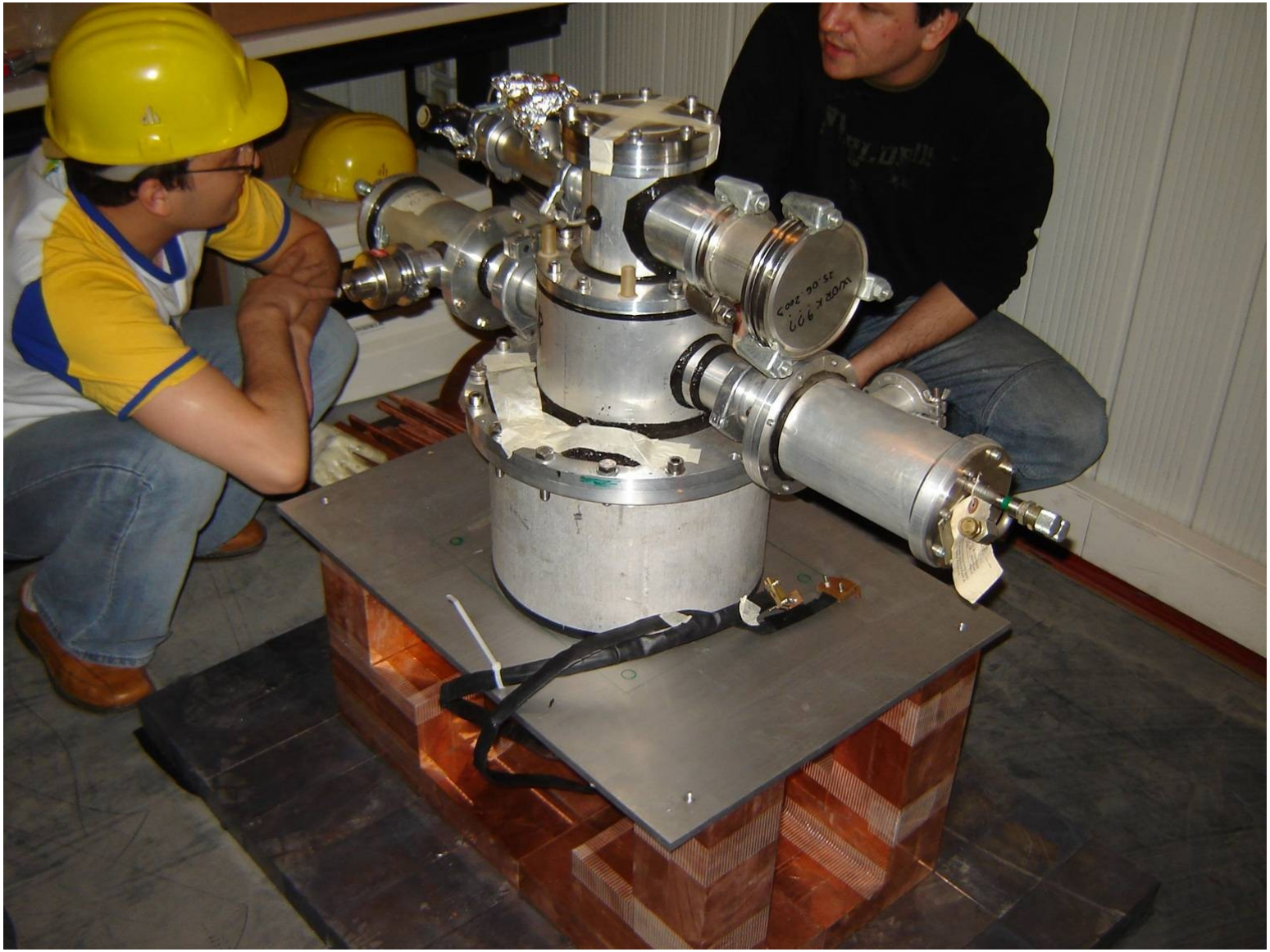
Phys. Lett. B 641 (2006) 18

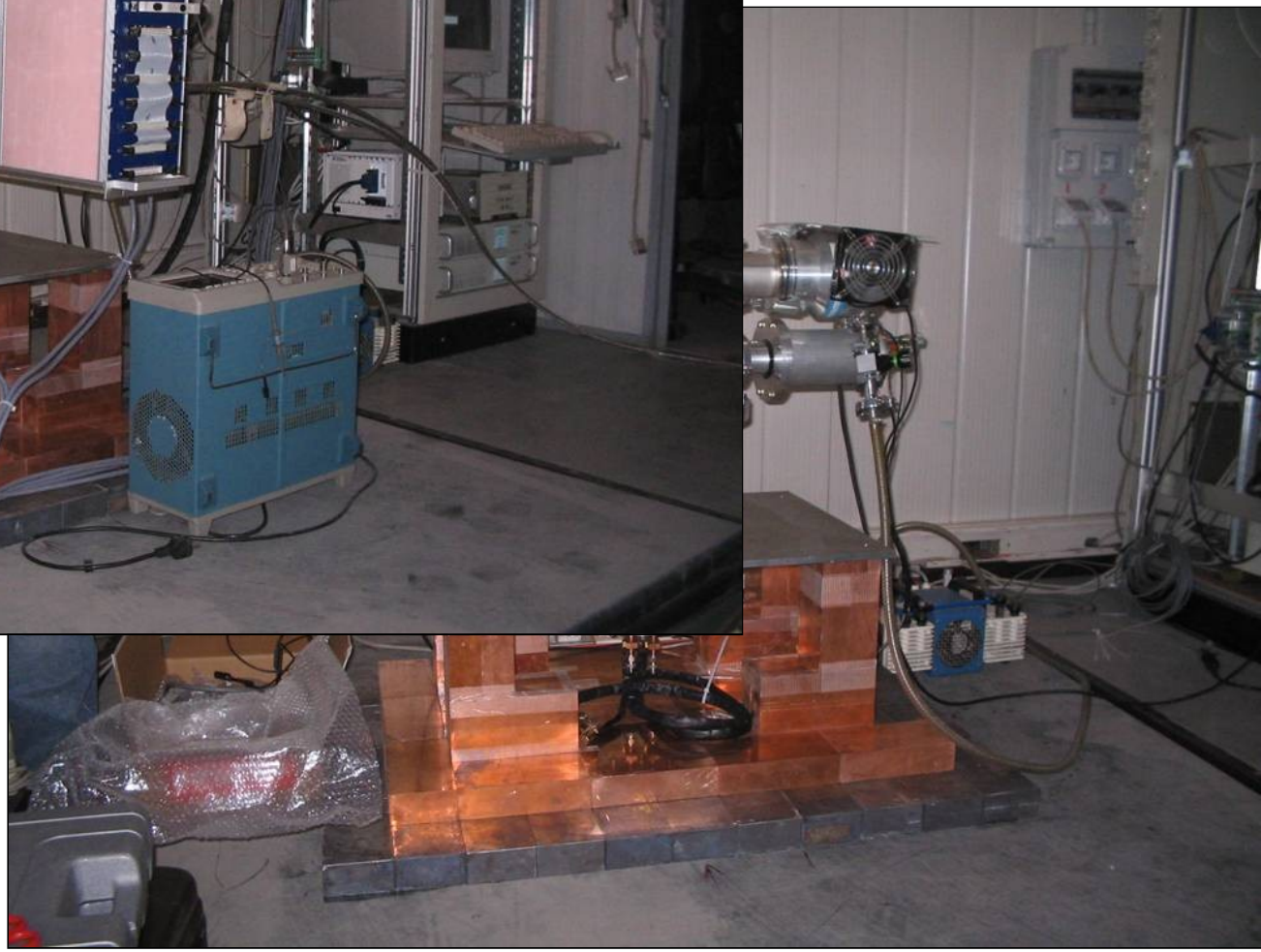
...ve get for the PEP violating parameter:

$$\beta^2/2 \leq 4.5 \times 10^{-28} \left(99.7\ C.L.\right)$$

Factor 40 of improvement of the limit obtained by Ramberg and Snow

Final setup at LNGS
February 2006





Shielding installation in April 2006

CRYOTIGER
IGG

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

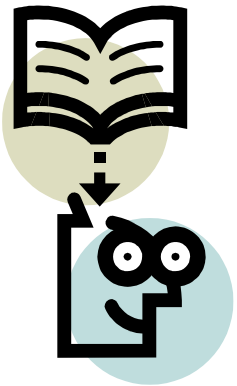
Preliminary LNGS results (January 2008) L. Sperandio Ph. D. Thesis

$$\beta^2/2 < 5.7 \times 10^{-29}$$

The VIP measurement will continue until the end of 2008 in the Gr Sasso-INFN underground laboratory, for bringing the limit of violation of the Pauli principle for electrons into the $10^{-29;-30}$ region

Spares

Interpretation of VIP data



The interpretation of this class of experiments is often the hardest part.

In the face of the importance of the Pauli Exclusion Principle, there are only few and incomplete theoretical constructs that allow for a violation.

At the root of the Exclusion Principle:
proof of spin-statistics theorem by Lüders and Zumino

Postulates:

- The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)
- Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality - microcausality)
- The vacuum is the state of lowest energy
- The metric of the Hilbert space is positive definite
- 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)

A possible – though at the moment unexpected – violation of PEP could point to new physics.

– in many quantum theories of gravity (most notably M-theory) nonlocality is expected at Planck scale

– nonlocality is present in theories with electron substructure

– a theory that incorporates the holographic principle could also lead to a violation of PEP: in fact "... the holographic principle calls into question not only the fundamental status of field theory, but the very notion of locality" (R. Busso, Rev. Mod. Phys. **74** (2002) 825)

electrons may be slightly "different"

This is suggested by the model of Biedenharn, Truini and van Dam (electrons as mixed states - this model has problems with the interpretation of high energy cross-sections)

In this case the IK phenomenology would hold and there would be low-rate X-ray emission and a current source COULD be useful (one could argue that the external electron reservoir could act as a source of electrons in the tensor two-particle state, this strongly depends on the unspecified mixing dynamics)

In this case the modulation provided by turning the current source on-off could be useful

(L. C. Biedenharn, P. Truini, and H. van Dam, J. Phys. **A22** (1989) L67)

Pauli exclusion principle

The Pauli Exclusion Principle (PEP) represents one of the fundamental principles of the modern physics and our comprehension of the surrounding matter is based on it. Even if today there are no compelling reasons to doubt its validity, it still spurs a lively debate on its limits, especially for those theories related to possible PEP violation coming from new physics.

- *There are several theoretical reasons to push the experimental limit in the region of 10^{-30} : for example the validity of Pauli principle in a higher-dimensional space-time with small violation in the 3+1 known dimensions, or strings and superstrings etc.*
-
- *"More recently … membrane theorists have been speculating on a large compactification radius for one of their eleven dimensions, which could give a ratio (for PEP violation) of 10^{-30}" [1]*
- *[1] I. Duck and E. C. G. Sudarshan: Towards an understanding of the spin-statistics theorem, Am. J. Phys, 66 (1998) 284.*

2008:

Feasibility test for VIP2

CCD -> SDD detectors

(triggerable) – shielding attivo

? Background reduction?

All invited to join!!!

Theoretical and experimental aspects of the spin-statistics connection and related symmetries

Stazione Marittima Conference Center
Trieste, Italy
21-25 october 2008

Organized by I.N.F.N. and by the University of Trieste, Italy

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For furher information:

e-mail: spinstat2008@ts.infn.it
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I-34127 Trieste, Italy.
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The workshop will focus on the spin-statistics connection and on related symmetries, both from the theoretical and from the experimental point of view. The workshop will bring together experimentalists, theorists, and philosophers to survey work done during the past years that challenges the traditional views of these issues. The workshop will also explore connections with rapidly developing fields such as other fundamental symmetries, supersymmetry and

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At the root of the Exclusion Principle: proof of spin-statistics theorem by Lüders and Zumino

Postulates:

- The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)
- Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality - microcausality)
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(G. Lüders and B. Zumino, Phys. Rev. **110** (1958) 1450)

Transition energies of the anomalous X-rays in Copper

Paul Indelicato (Ecole Normale Supérieure et Université Pierre et Marie Curie)

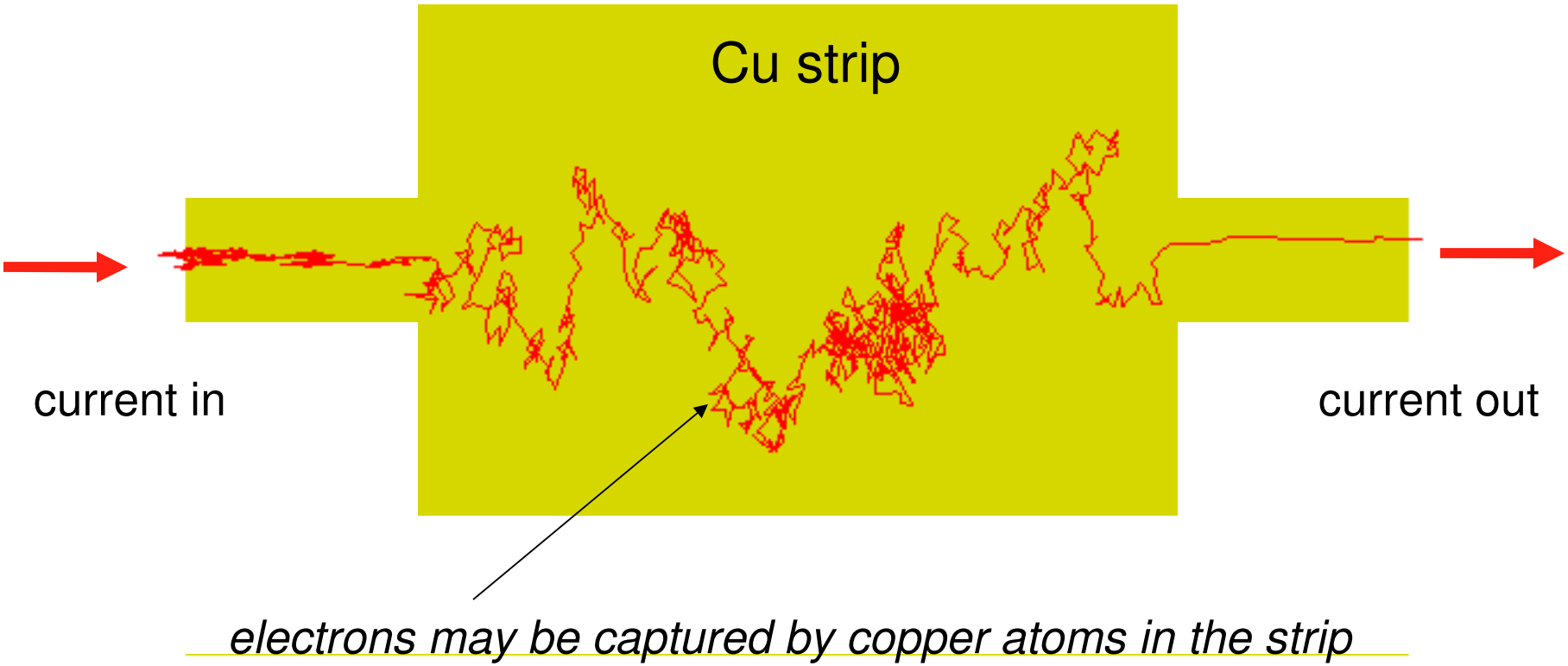
Multiconfiguration Dirac-Fock approach

core: (1s)2(2s)2(3s)2(2p)2(3p*)2(2p)4(3p)4(3d*)4(3d)*

Transition	Initial en.	Final en.	Transition energy	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 copper: ~ **8040 eV (2p → 1s)**
- **Note: similar value obtained by S. Di Matteo e L. Sperandio in the "sudden approximation".**

random walk of the conduction electrons in the copper strip



Ramberg & Snow calculation

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

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

$$D = 0.025\, m$$

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

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

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

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

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

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

The parameter β

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

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

through the following relations:

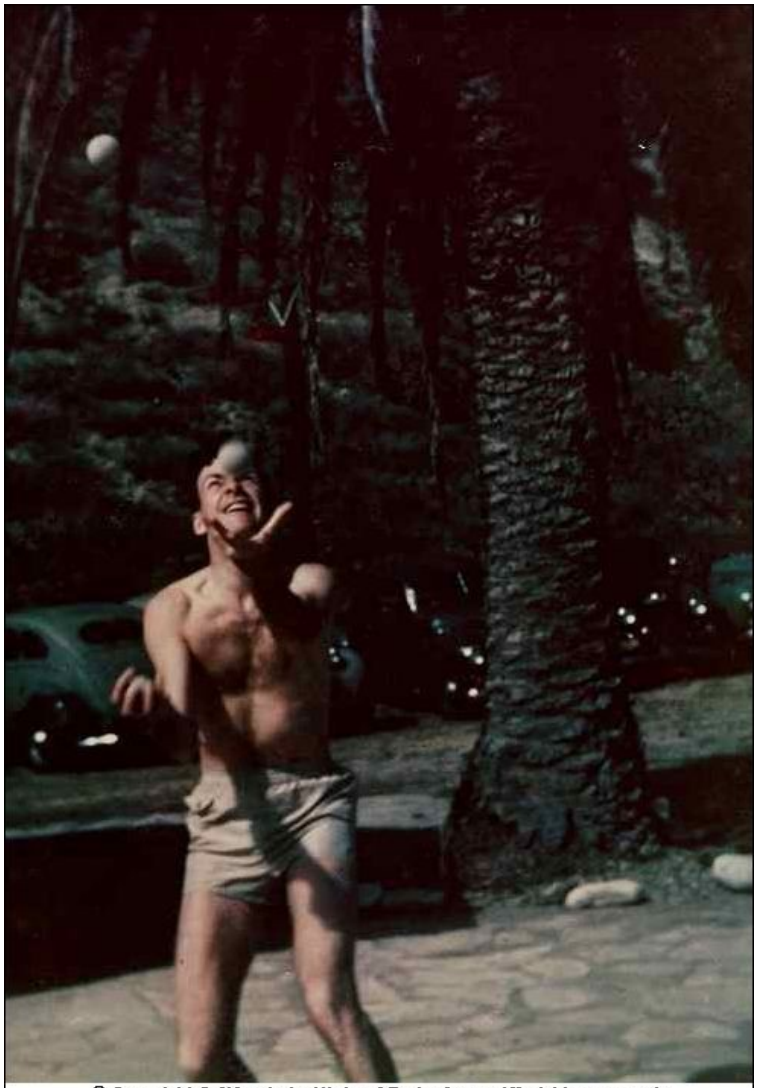
$$a^{+}|0|1 \qquad a|0\,0$$

$$a|1$$

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

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

Feynman Lectures on Physics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This brings up an interesting question: 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. For the moment, you will just have to take it as one of the rules of the world

VIP results LNGS

Analyses of data taken at LNGS with shielding :

236005 min @ I=40A

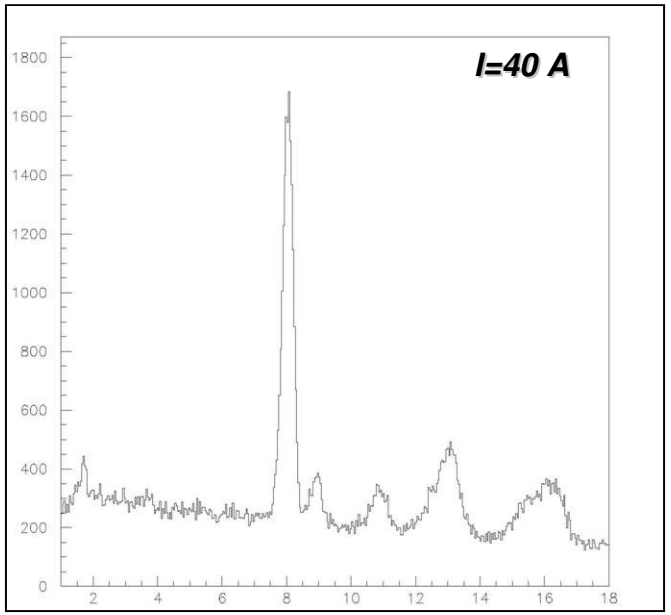
172685 min @ I=0A

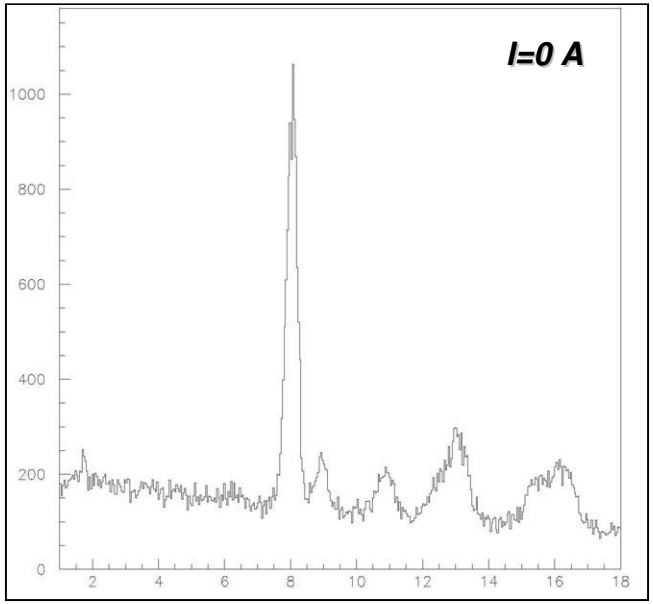
(CCD read every 5 min)

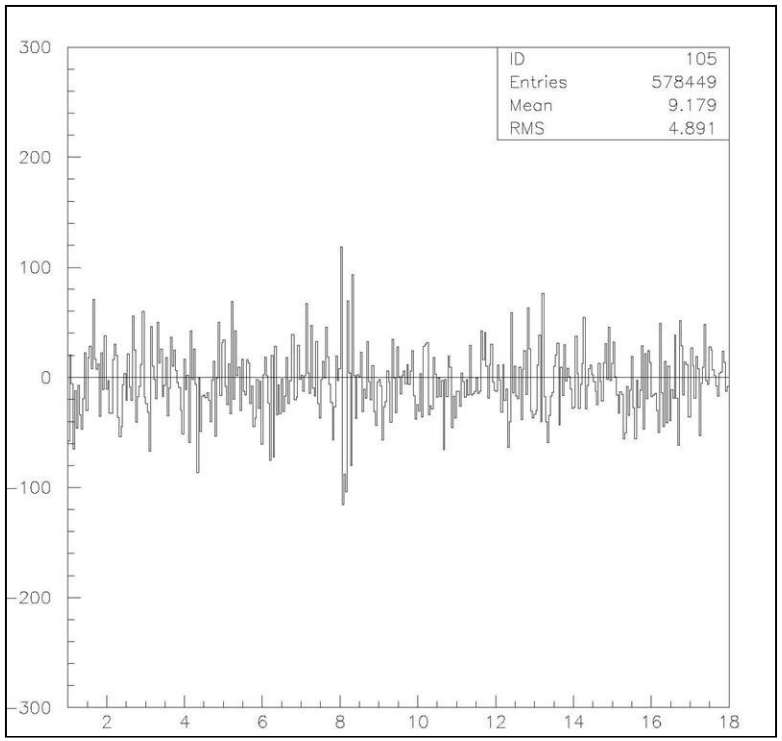
Apr – Nov 2006 (I)	Gen – May 2007 (II)
142905 min @ I=40A 84430 min @ I=0A	93100 min @ I=40A 88255 min @ I=0A

- *Two sub-periods analyzed separately because of different DAQ condition*

First period (Apr. – Nov. 2006)







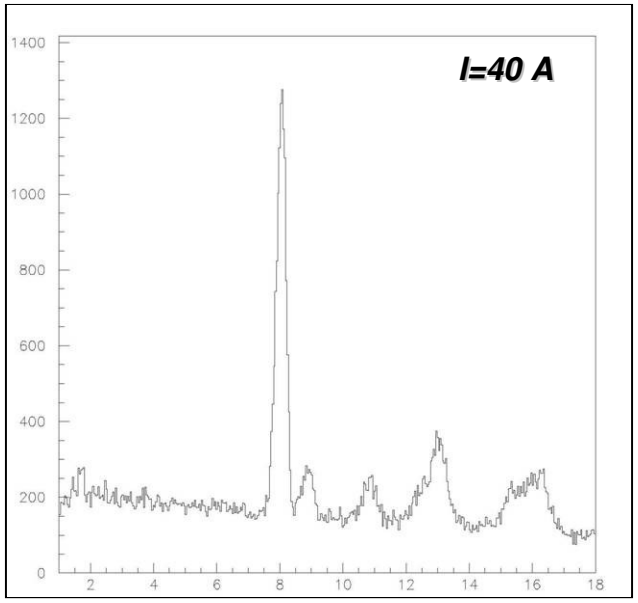
C=1.693

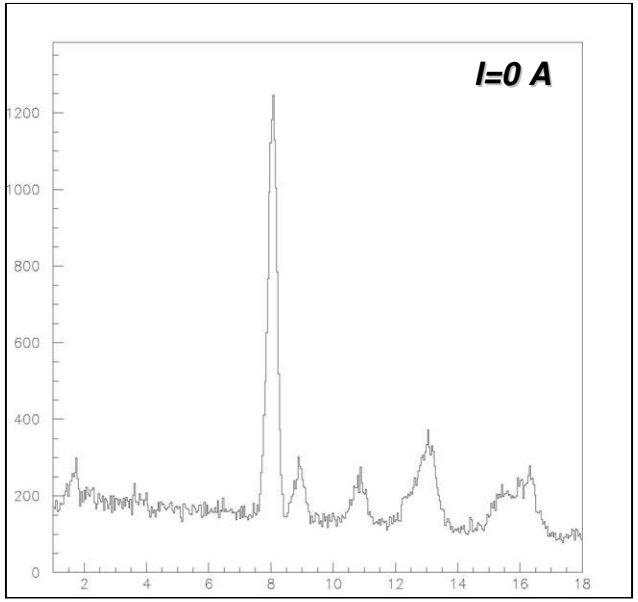
ROI= (7.53 ÷ 7.93) KeV

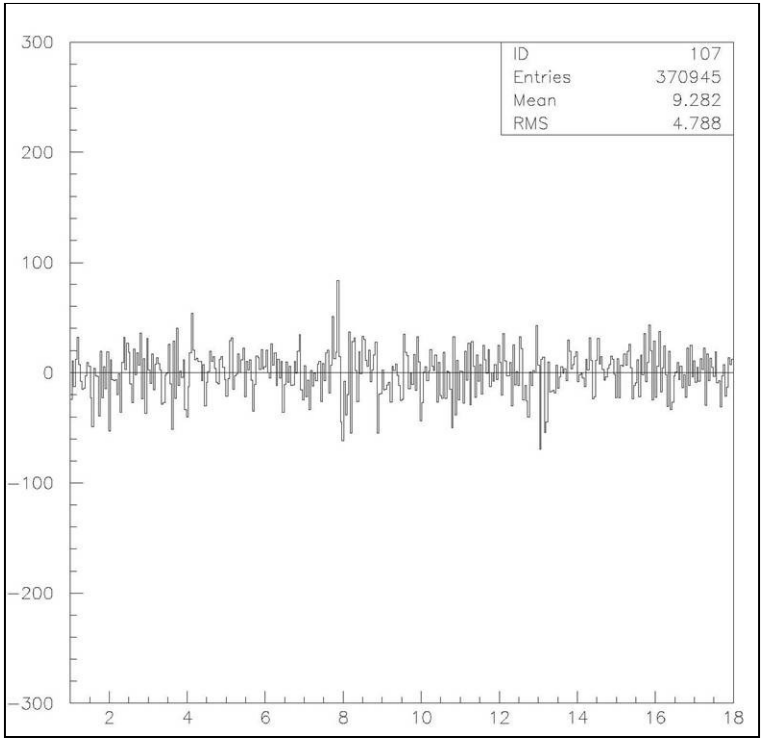
$N_\chi+\varepsilon_\chi = 5751 \pm 76$ @ I=40A

$N_\chi+\varepsilon_\chi = 3406 \pm 58$ @ I=0A

Second period (Gen. – May 2007)







C=1.055

ROI= (7.53 ÷ 7.93) KeV

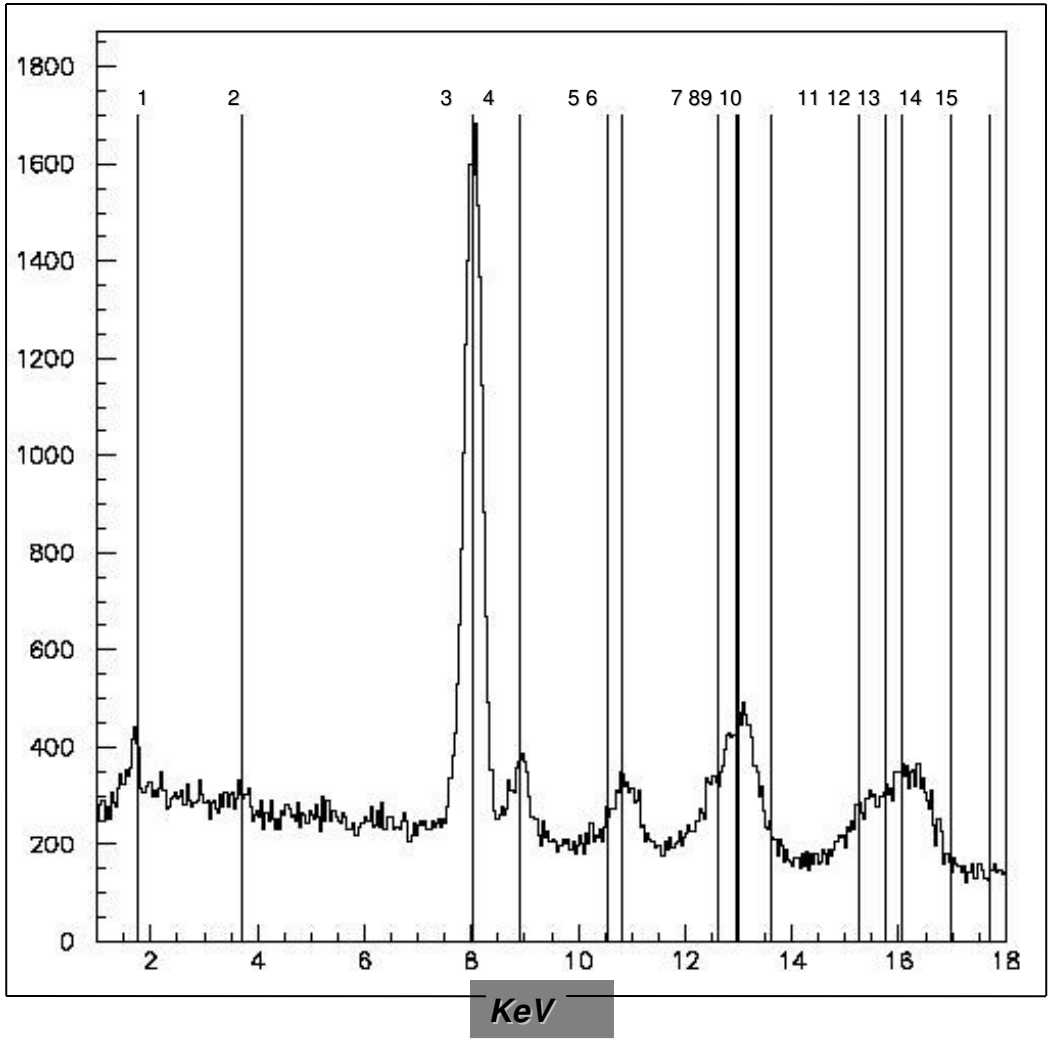
$N_\chi+\varepsilon_\chi = 3866 \pm 62$ @ I=40A

$N_\chi+\varepsilon_\chi = 3471 \pm 59$ @ I=0A

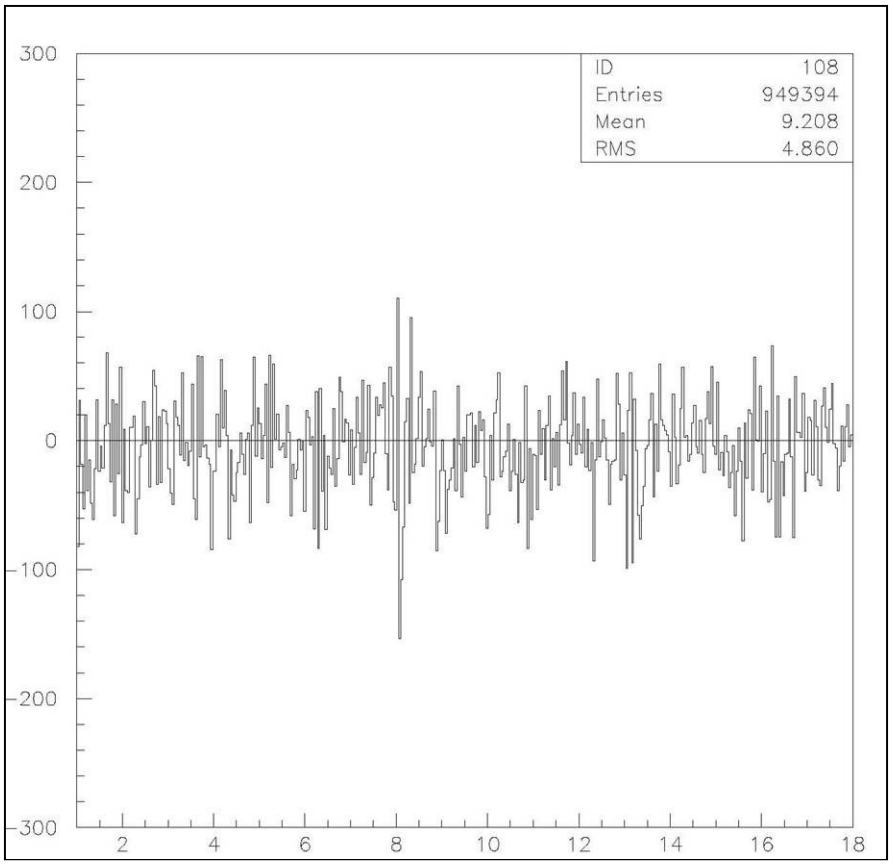
The study of background

I=40A ; T=142905 min. ; N_{ev} (1÷18 KeV)=117300

Line	*Element*	*Energy (KeV)*
1	K_α (Si)	1.74
2	K_α (Ca)	3.69
3	K_α (Cu)	8.04
4	K_β (Cu)	8.91
5	L_α (Pb)	10.54
6	L_α (Bi)	10.83
7	L_β (Pb)	12.62
8	L_α (Th)	12.95
9	L_β (Bi)	13.01
10	L_α (U)	13.60
11	L_γ (Bi)	15.25
12	K_α (Zr)	15.75
13	L_β (Th)	16.04
14	L_β (U)	16.98
15	K_β (Zr)	17.70



The best limit !



$N_X+\varepsilon_X = 190 \pm 152$

Performing the calculation we find for the PEP violation parameter :

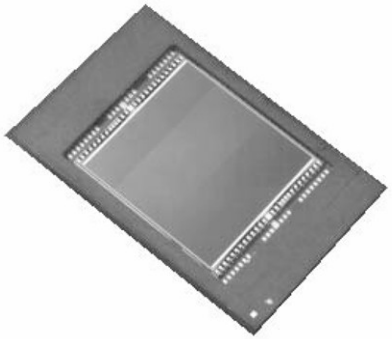
$$\frac{\beta^2}{2} \leq \frac{3 \cdot 152}{79.72} \cdot 10^{-29}$$

$$\beta^2/2 \leq 5.72 \times 10^{-29}$$

We have thus improved the limit obtained by Ramberg & Snow by a factor ~ 250 (about 3 orders of magnitude)

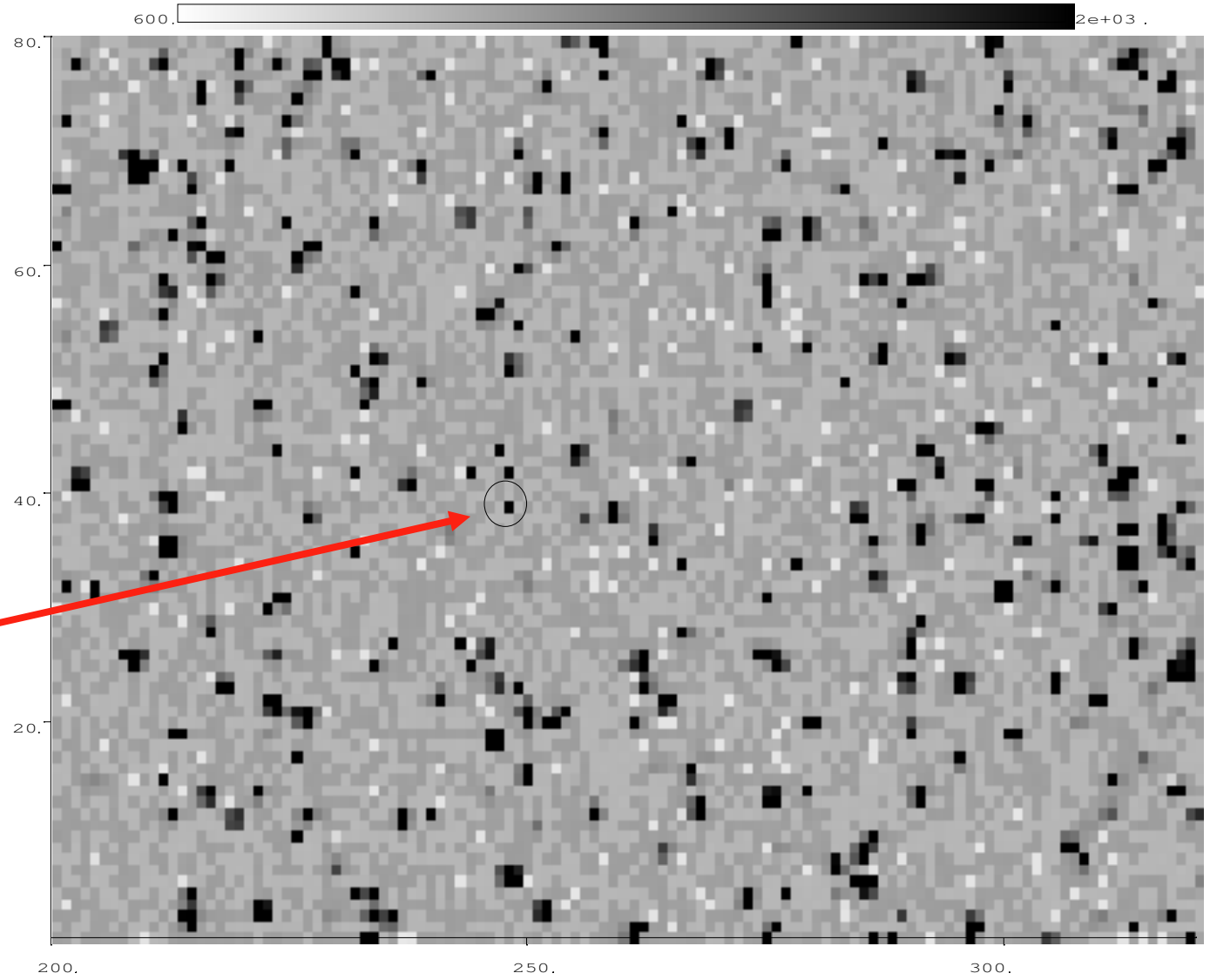
"New limit on the Pauli Exclusion Principle violation by electrons", L. Sperandio et al., IL NUOVO CIMENTO (in press)

CCD's, the "secret weapon" of the VIP experiment ...



EEV CCD55
(1252 x 1152 pixels,
22.5 µm x 22.5 µm)

single pixel event,
X-ray photon



(for details on data analysis see Ishiwatari et al, NIM A556 (2006) 509)

First results

@ I=40A → Nx= 2721 ± 52

@ I=0A → Nx= 2742 ± 52

$$N_X \geq 4.9 \times 10^{29}\ \beta^2$$

We get for the PEP violating p

$$\beta^2/2 \leq 4.5 \times \quad (99.7\ C.L.)$$

Phys. Lett. B 641 (2006) 18

tor 40 of improvement of the limit obtained by Ramberg and Snow

Theories of Violation of Statistics

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. Of these (a) seems unlikely because the quon theory which obeys CPT allows violations, (b) seems likely because if locality is satisfied we can prove the spin-statistics connection and there will be no violations, (c), (d), (e) and (f) seem possible……..

Hopefully either violation will be found experimentally or our theoretical efforts will lead to understanding of why only Bose and Fermi statistics occur in Nature."