Search for the Pauli Exclusion Principle violating electrons at LNGS

Hexi Shi

Stefan Meyer Institute for Subatomic Physics,
Austria Academy of Science,Vienna

On behalf of the VIP-2 collaboration

29 April 2014
LNF-INFN, Frascati

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Motivation
- in the words of W. 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

overview

- Pauli Exclusion Principle - presentations
- Violation of fermi- and bose- statistics
- How to *search* for small amount of violation?
- VIP experiment and result

VIP-2 experiment

- upgrade in VIP-2
- preparation status

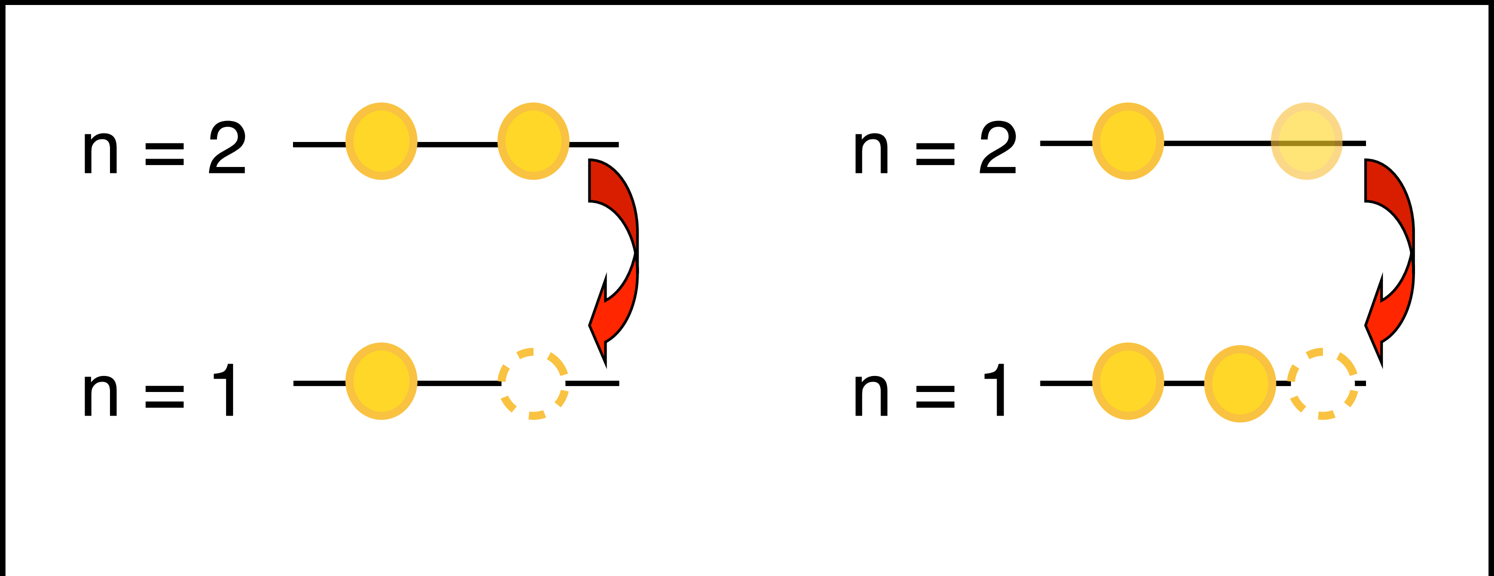
Pauli Exclusion Principle - in its original form

"In an atom there cannot be two or more equivalent electrons for which the values of all four quantum numbers coincide. If an electron exists in an atom for which all of these numbers have definite values, then the state is occupied. "

W. Pauli, Zeitschrift für Physik 31(1925) 765.

How to search for violation?

a most intuitive picture:



Normal 2p→1s transition

2p→1s transition violating Pauli Principle

8.05 keV for Cu

~ 7.7 keV for Cu

anomalous transition X-rays from atomic states

Other presentations

In QM

> "The states of a system containing N identical particles are necessarily either all symmetrical or all anti-symmetrical with respect to permutations of the N particles."

Messiah and Greenberg (1964), Symmetrization postulate

plus measurements that fix the symmetry of many-particle wavefunctions

In QFT

Fermi statistics for spin-half particles

anti-symmetric states: one particle per quantum state

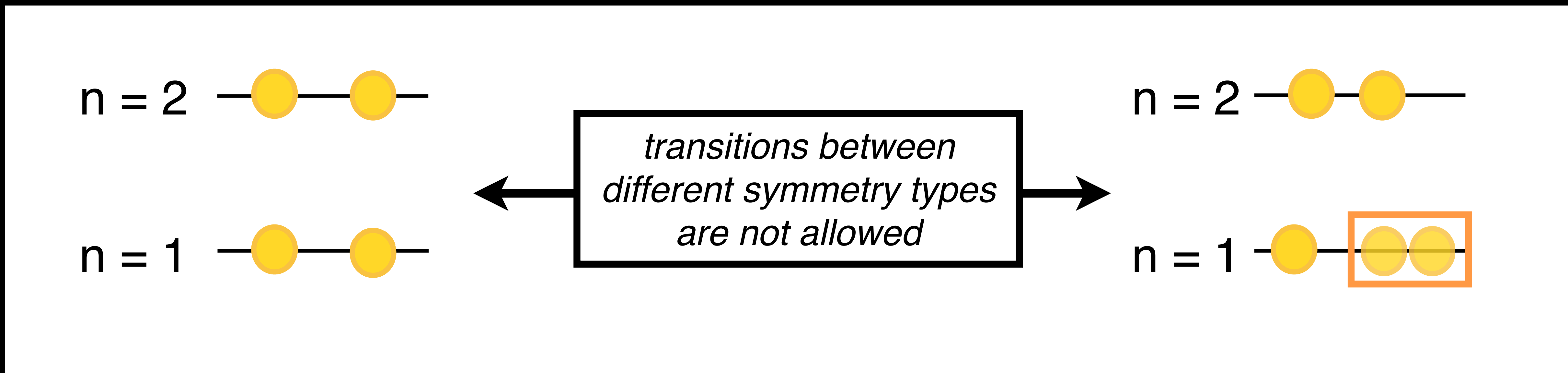
Bose statistics for integral spin particles

symmetric many particles in the same quantum state

Can there be states with *mixed symmetry* which have a small violation to fermi-statistics?

G. Gentile, Nuovo Cimento **17**, 493 (1940). H. Green, Phys. Rev **90**, 270 (1953).
O. Greenberg and R. Mohapatra, Phys. Rev. Lett. **59**, 2507 (1987).
O. W. Greenberg, in *Spin-Statistics Connection and Commutation Relations* (AIP, 2000), pp. 113–127.

How to search for violation? - again

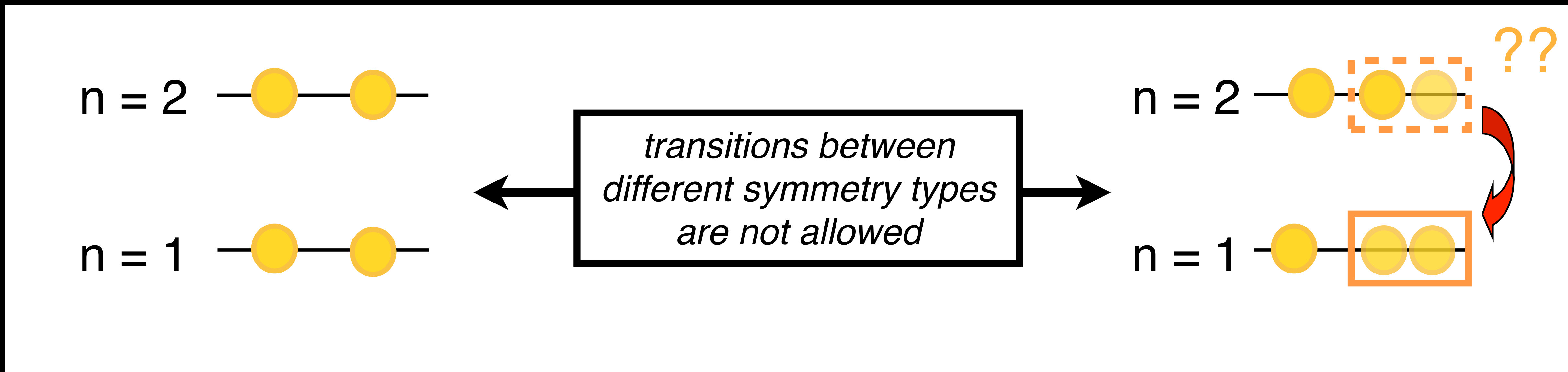


ground state for fermi statistics

ground state for PEP-violating statistics: with “mixed” symmetry

how to search for such states, and how to parameterize, if a tiny amount of violation exists?

How to search for violation? - again



ground state for fermi statistics

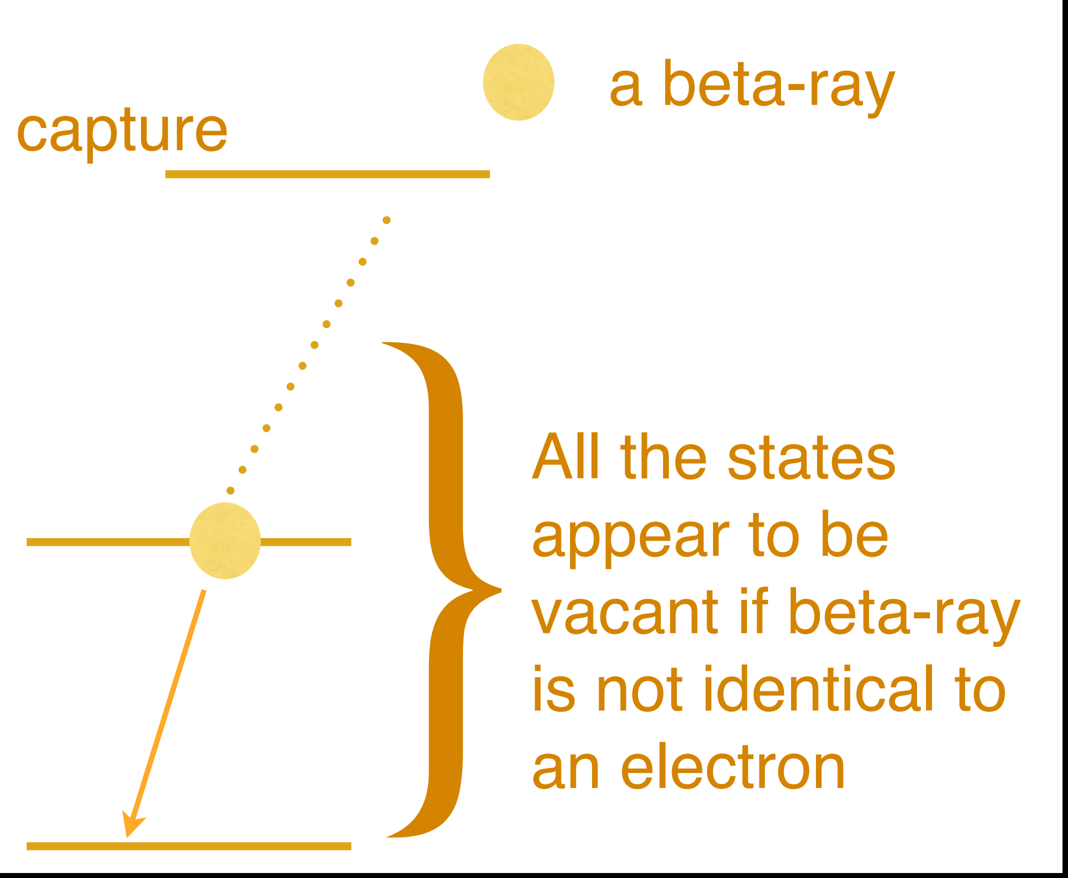
ground state for PEP-violating statistics: with “mixed” symmetry

how to search for such states, and how to parameterize, if a tiny amount of violation exists?

Goldhaber & Scharff-Goldhaber experiment

"Are the electrons from nuclear beta decay same as electrons in atoms?"

Goldhaber experiment : shed electrons from ^{14}C source on lead foil. Estimated limit for PEP violation: *~ 3 x 10^{-2}*



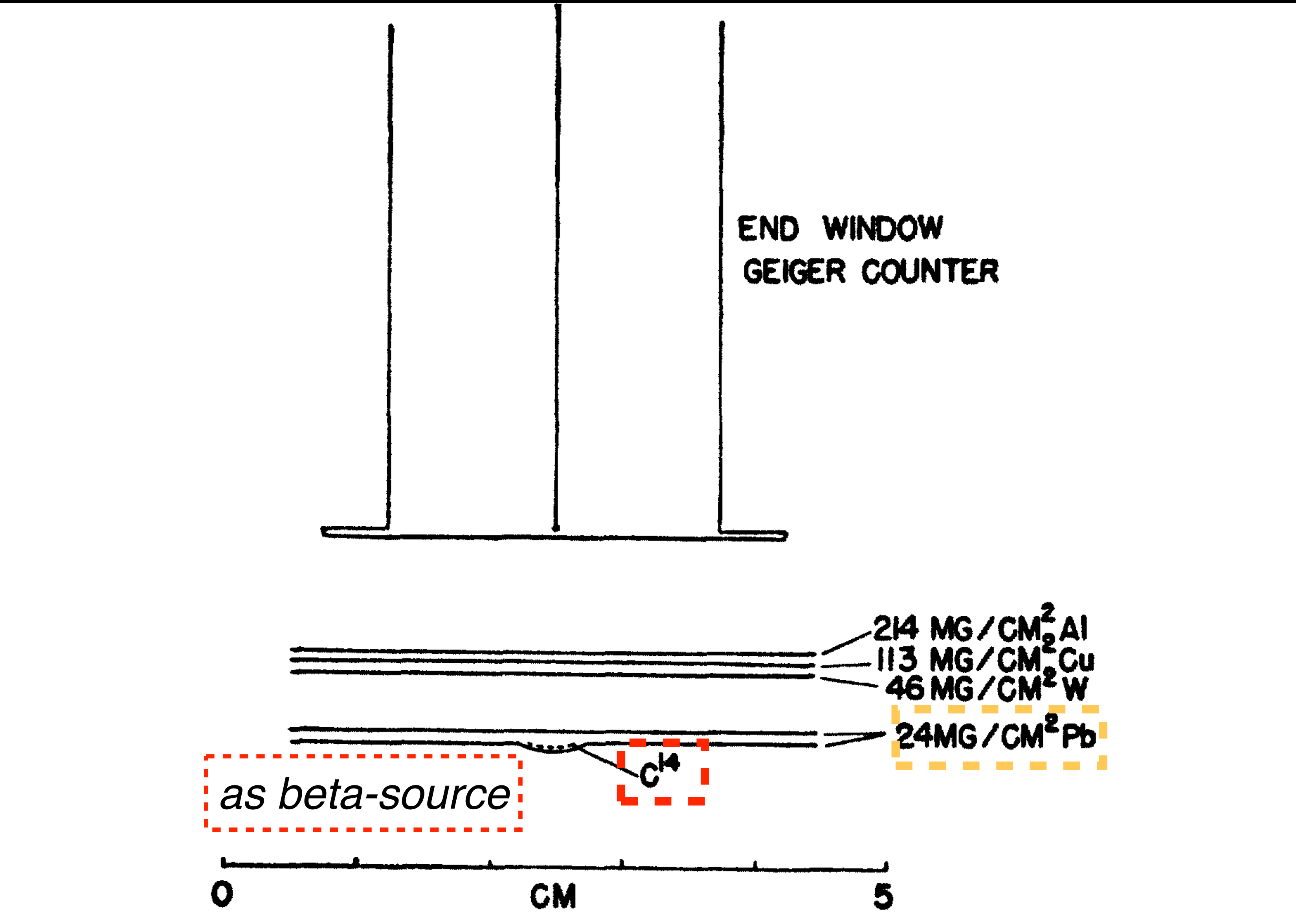
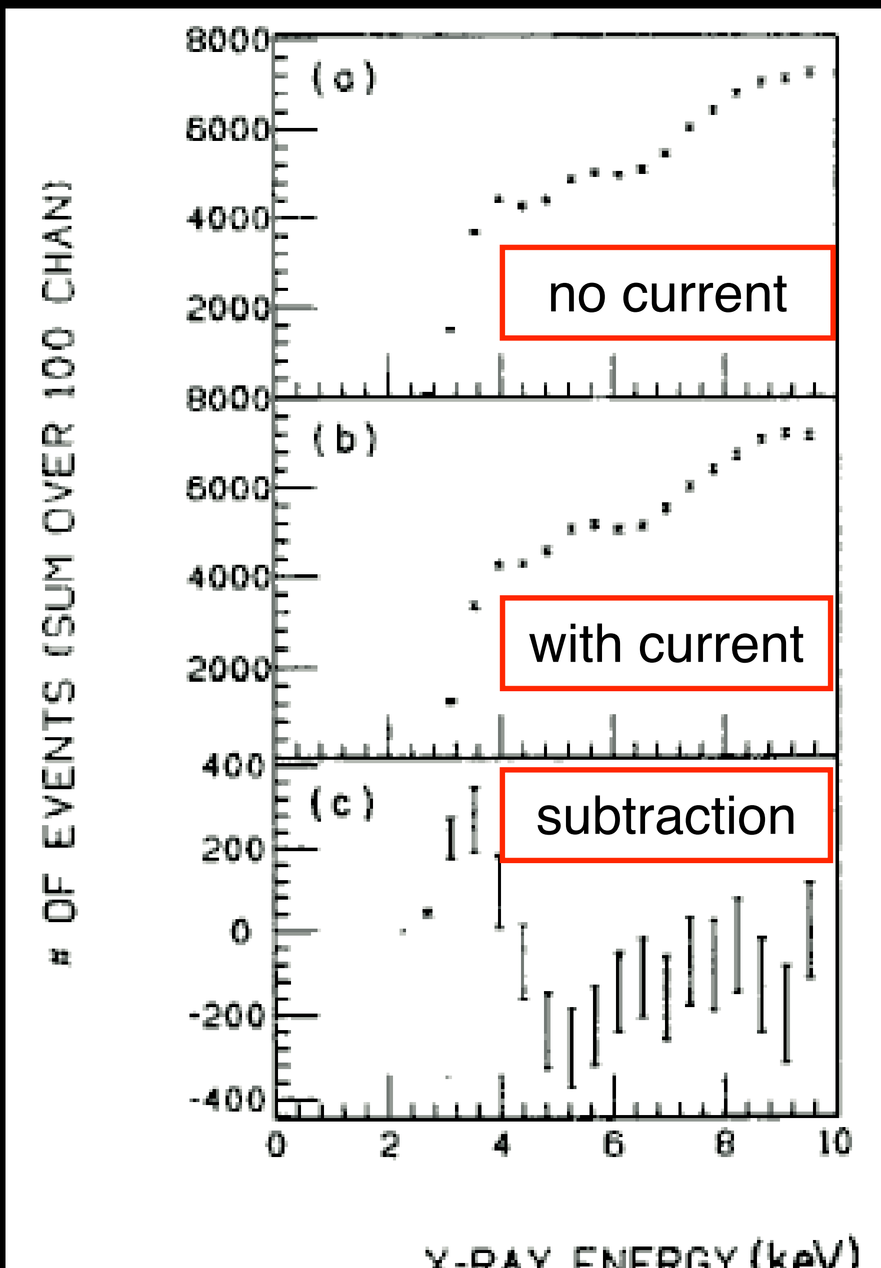


FIG. 1. Arrangement used in search for photons from beta-rays stopped in lead.

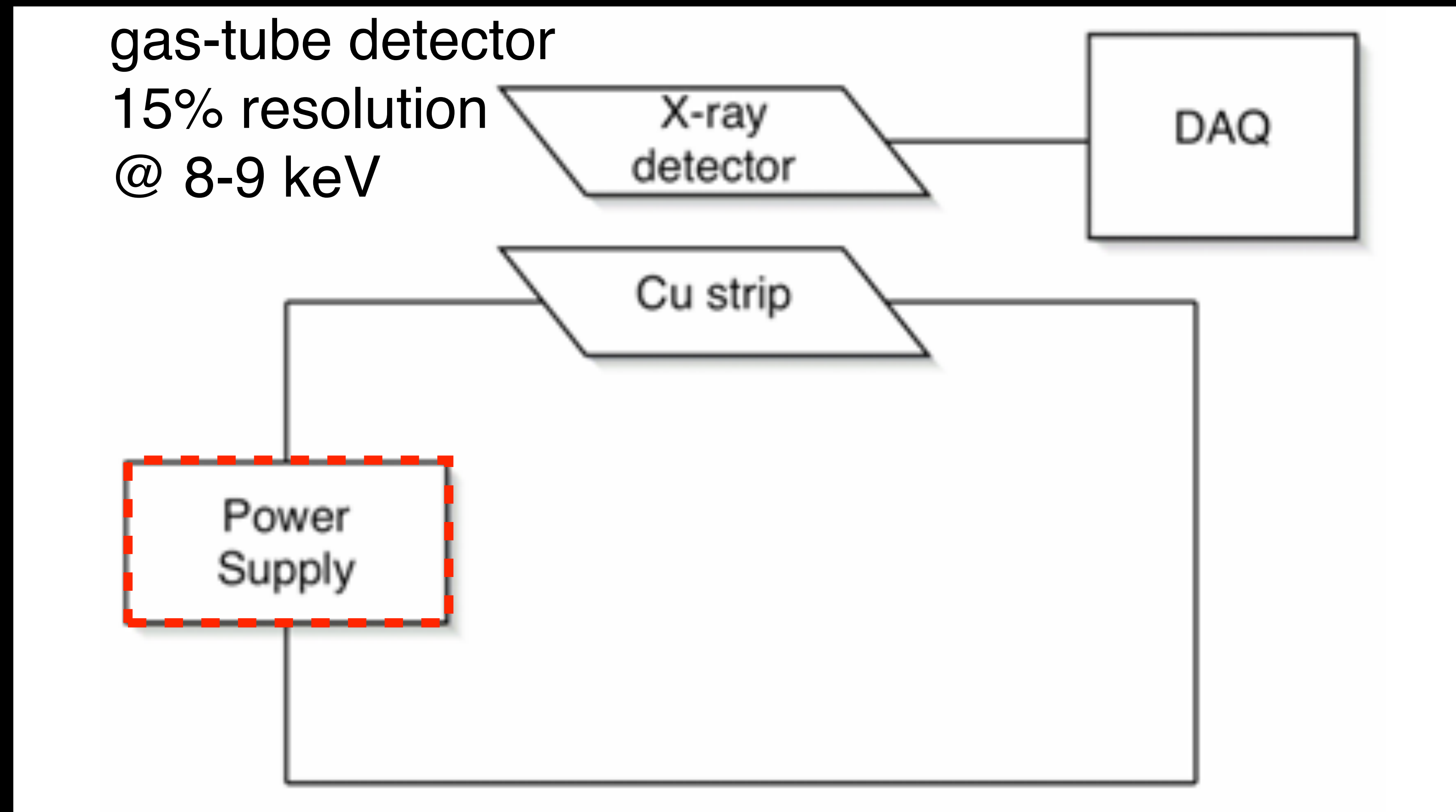
M. Goldhaber and G.S. Goldhaber, Phys. Rev. 73 (1948) 1472

Ramberg - Snow experiment

Introduce “new” external electrons by a circulating current to a conducting (Cu) strip, and search for anomalous transition X-rays



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



$$N_X \geq \frac{1}{2}\beta^2 N_{new} \frac{N_{int}}{10}$$

$\beta^2 / 2 <= 1.7 \times 10^{-26}$ *(> 95% C.L.)*

probability of “mixed symmetry state”

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:

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

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

The VIP (<u>**VI**</u>olation of the <u>**P**</u>auli Principle) experiment

Goal

to improve the limit on the probability of a possible violation
of the Pauli exclusion principle for electrons,
set in Ramberg-Snow experiment

by means of

- sensitive, large-area, X-ray detectors:
  Charge Coupled Device (CCD)
- clean, low-background experimental area (LNGS)

Experiment apparatus

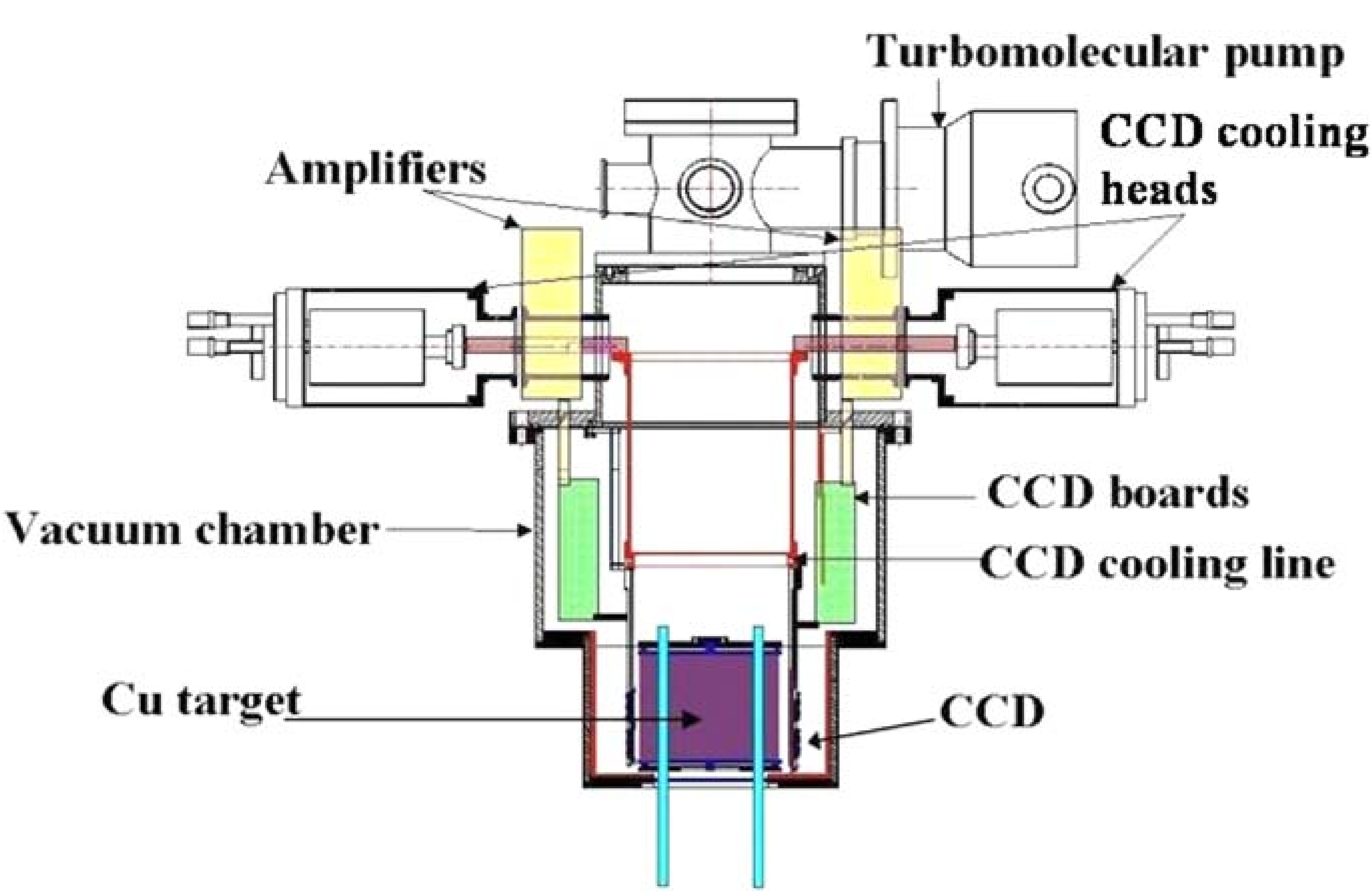
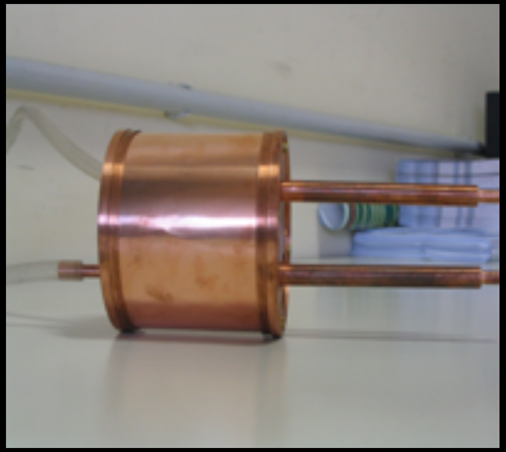


Fig. 1. The VIP setup. All elements at the setup are identified in the figure.

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

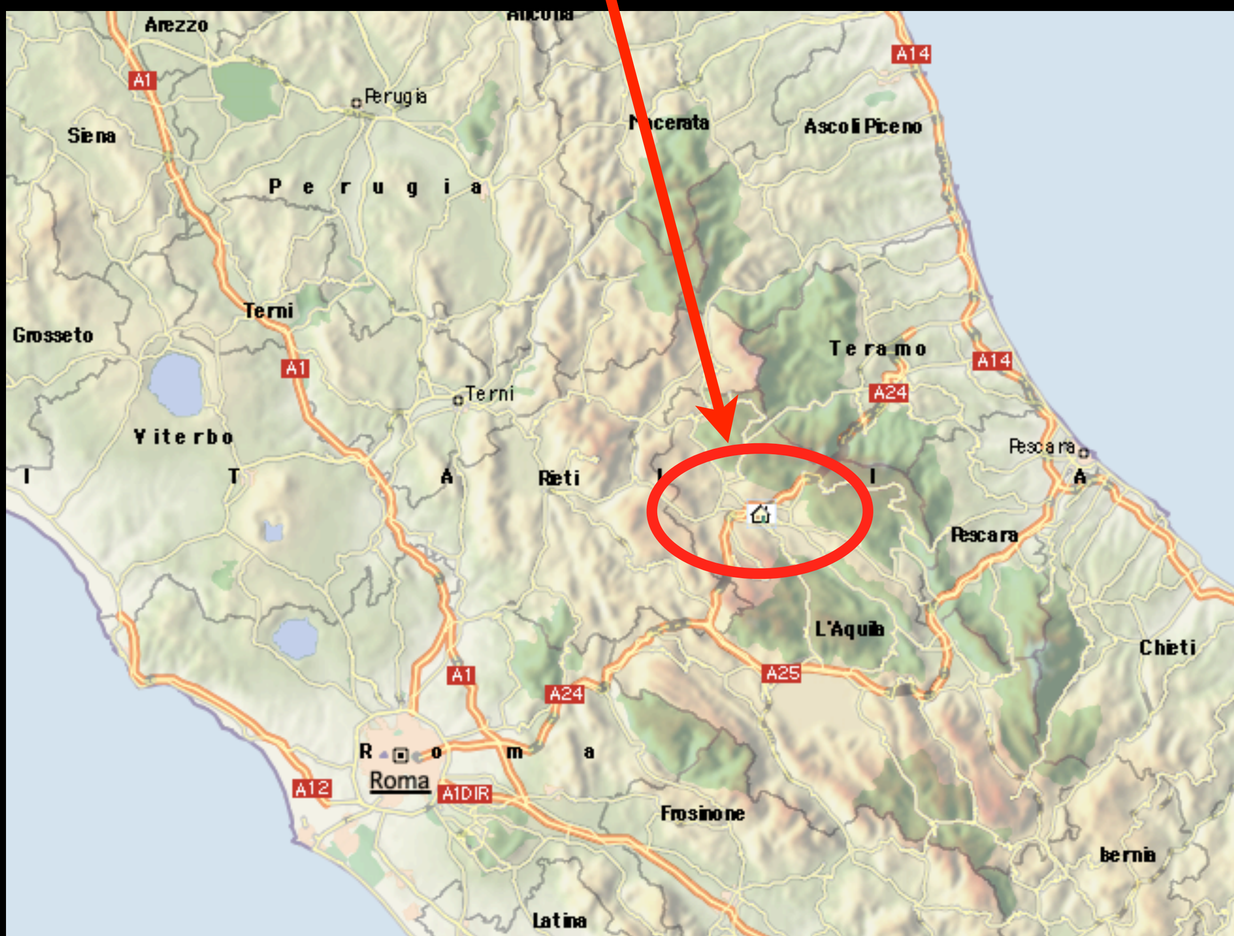
Experiment setup - 2

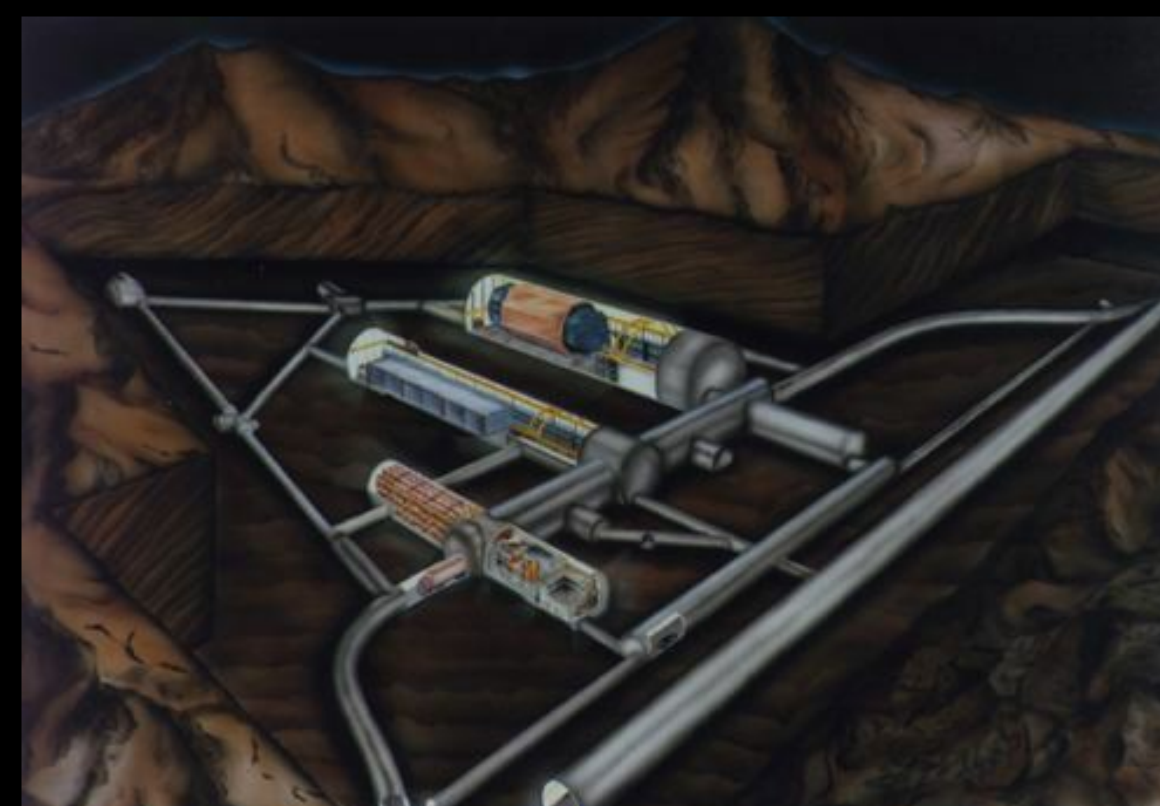
Cu target



Experiment site at Gran Sasso (LNGS)

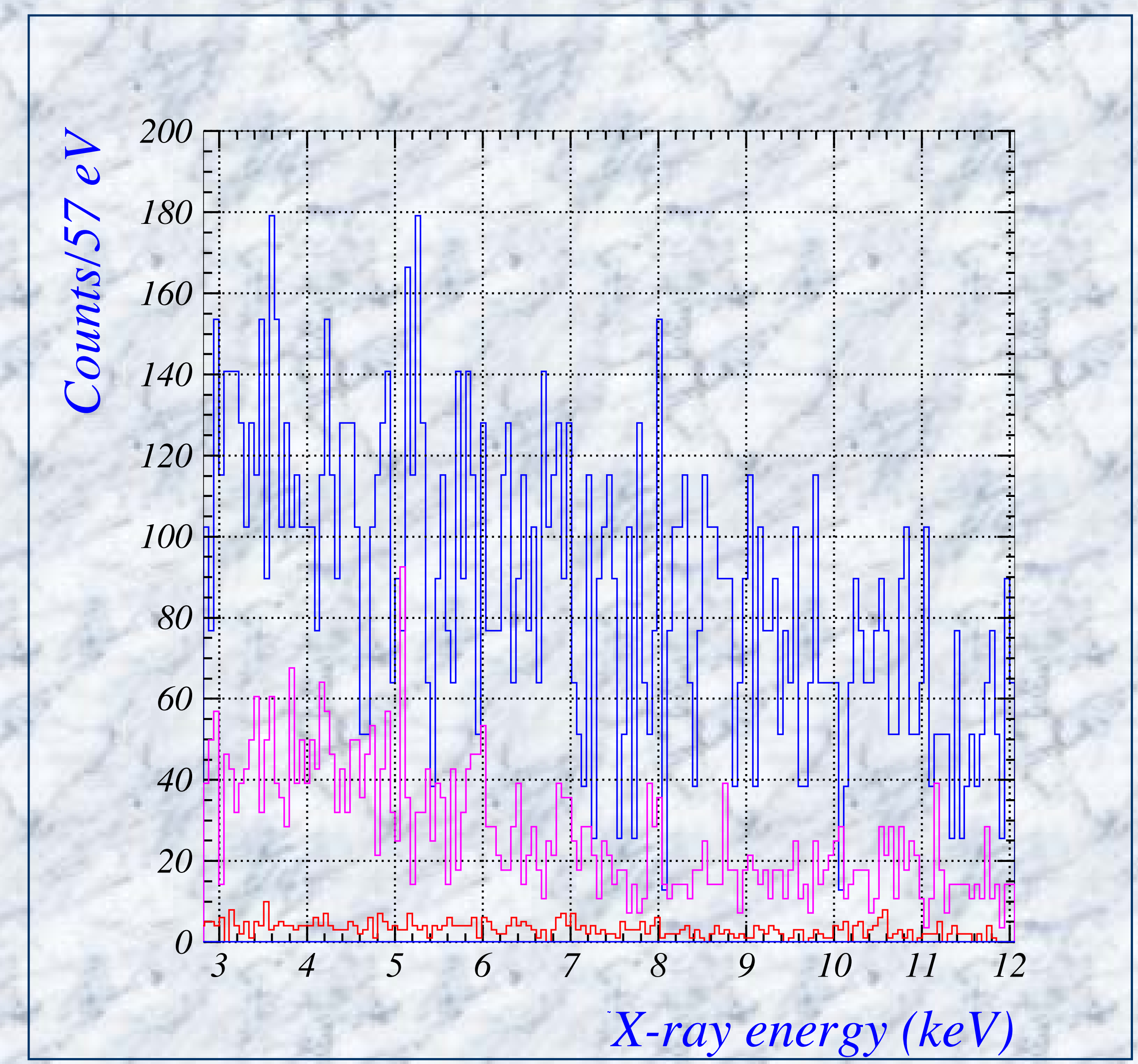
Laboratori Nazionali del Gran Sasso (LNGS),
Istituto Nazionale di Fisica Nucleare





Background reduction at LNGS

Why at LNGS ?



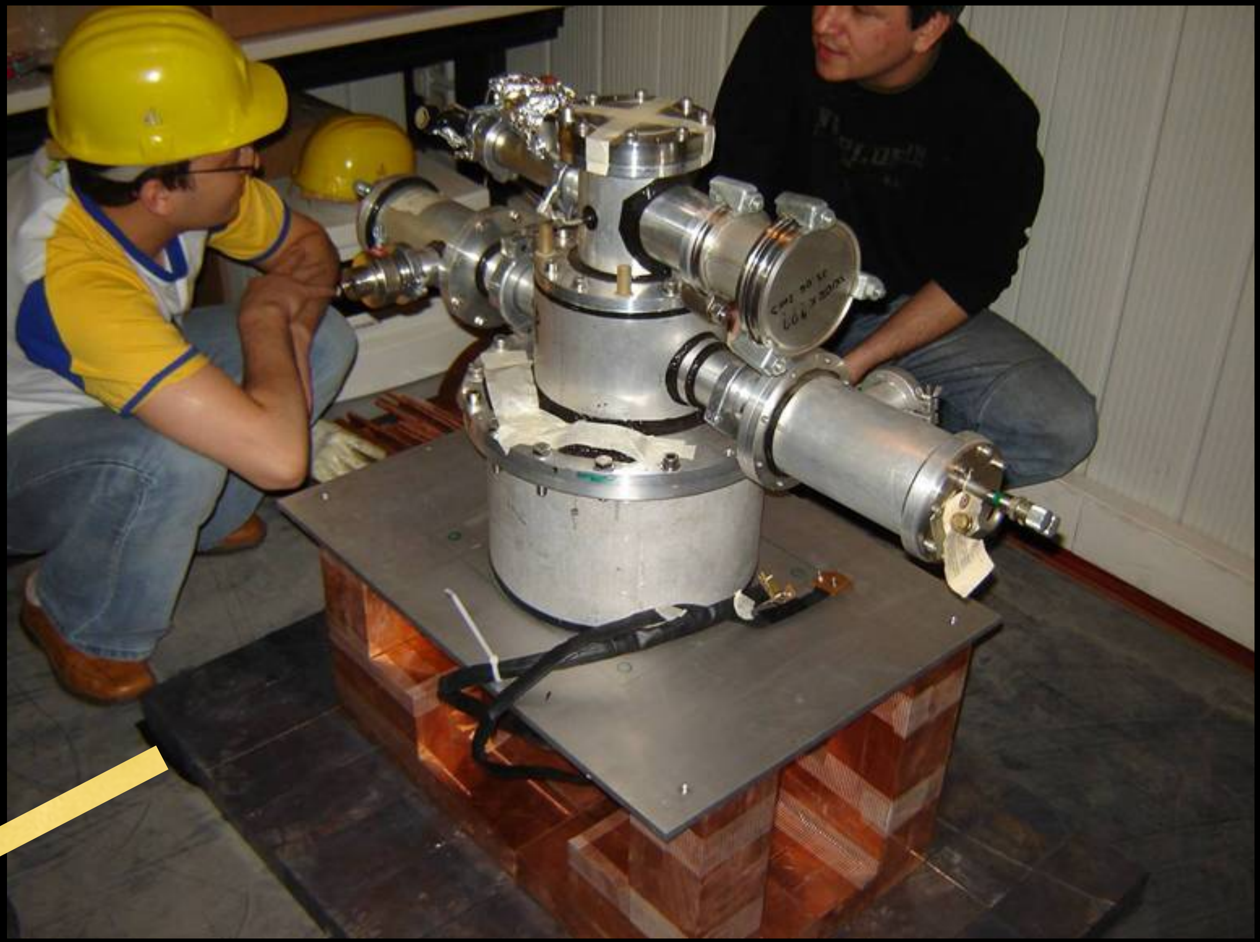
2 CCD test setup – normalized distributions

- **Lab no sh.**
- **Lab with sh.**
- **LNGS with sh.**

Background reduced by a factor ~ 20

L. Sperandio, 2007

The VIP setup at LNGS



First results of VIP

two types of measurements, same time span

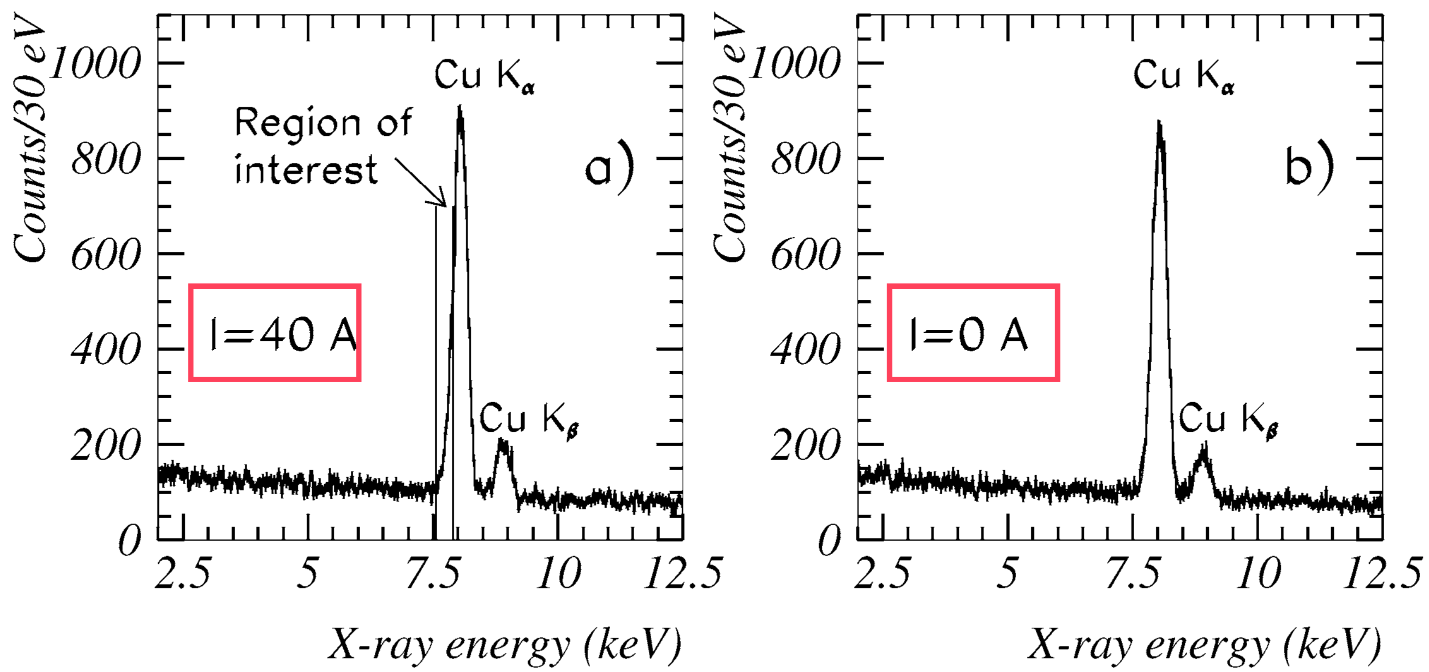
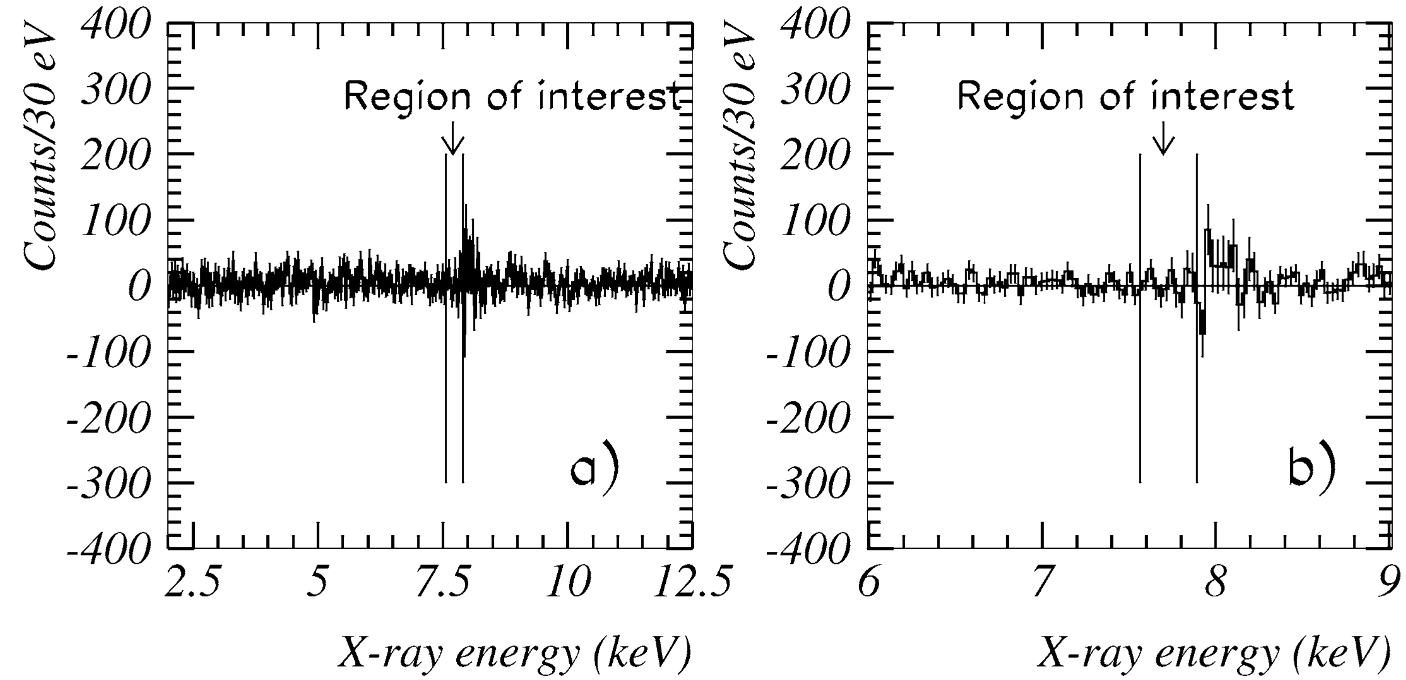


Fig. 2. Energy spectra for the VIP measurements: (a) with current ($I = 40$ A); (b) without current ($I = 0$).

subtraction at ROI gives :
- 21 ± **73** events



$$\frac{\beta^2}{2} \leqslant \frac{3 \times 73}{4.9 \times 10^{29}} = 4.5 \times 10^{-28} \quad \text{at } 99.7 \text{ CL.}$$

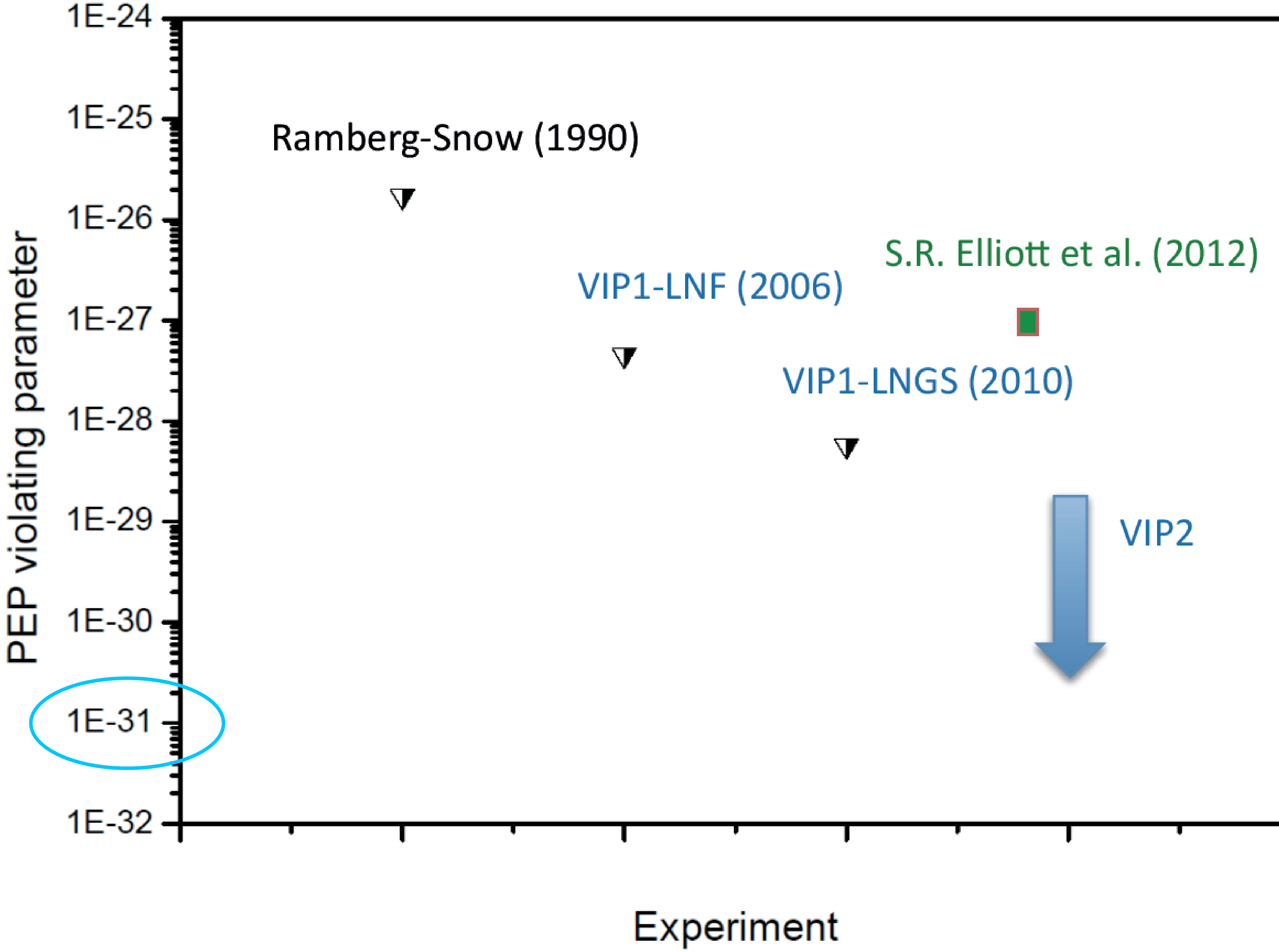
S. Bartalucci, et. al, Physics Letters B **641**, 18 (2006).

A summary of previous limits

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

Process	Type	Experimental limit	$\frac{1}{2}\beta^2$ limit	
Atomic transitions				
$\beta^- + \text{Pb} \to \check{\text{P}}\text{b}$	Ia	recently created fermions (electrons)	3×10^{-2}	Goldhaber 1948
$e^-_{pp} + \text{Ge} \to \check{\text{G}}\text{e}$	Ia		1.4×10^{-3}	
$e^-_I + \text{Cu} \to \check{\text{C}}\text{u}$	II	distant fermions (electrons)	1.7×10^{-26}	Ramberg 1990
$e^-_I + \text{Cu} \to \check{\text{C}}\text{u}$	II		4.5×10^{-28}	VIP 2006
$e^-_I + \text{Cu} \to \check{\text{C}}\text{u}$	II		6.0×10^{-29}	VIP 2011
$e^-_I + \text{Pb} \to \check{\text{P}}\text{b}$	II		1.5×10^{-27}	S.R. Elliott 2012
$e^-_f + \text{Pb} \to \check{\text{P}}\text{b}$	IIa		2.6×10^{-39}	

Towards VIP-2



J. Marton, et. al, JoP: Conference Series **447**, (2013)012070.

VIP-2 experiment designs and status

The VIP-2 Collaboration

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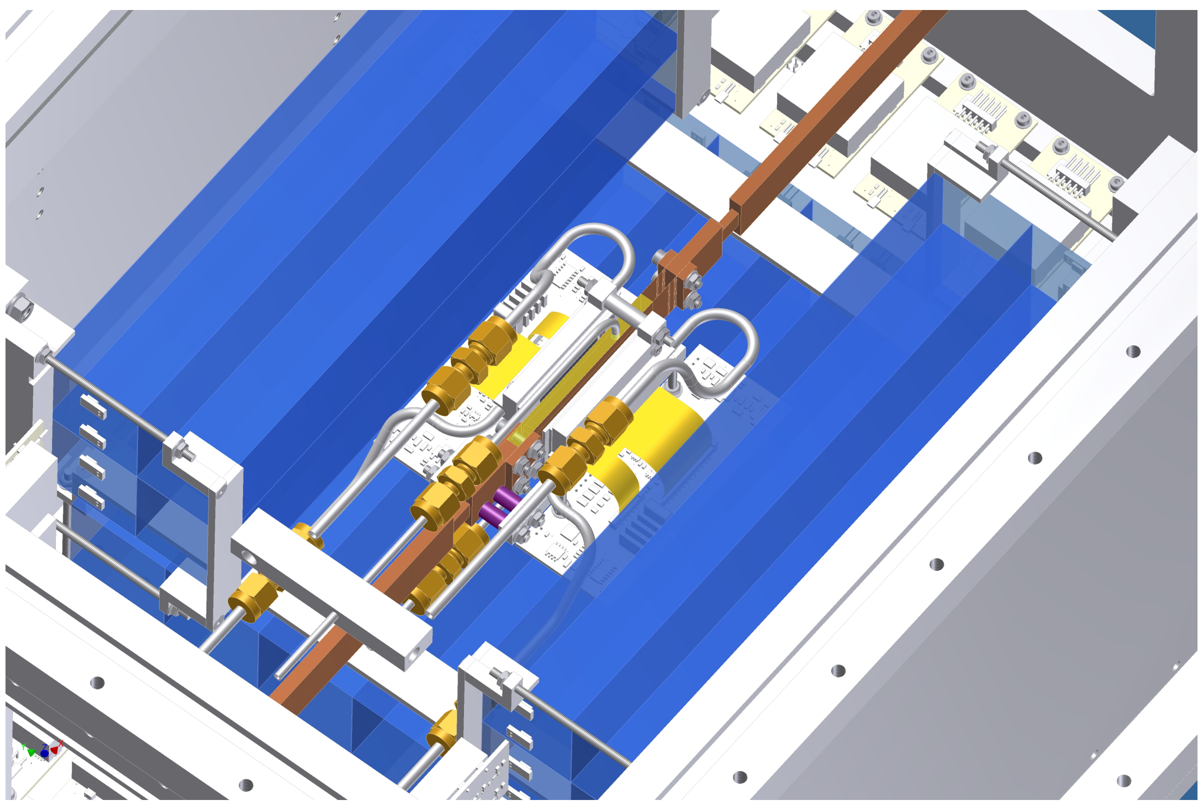
O. Vazquez Doce
Excellence Cluster Universe, Technische Universität München, - Garching, Germany

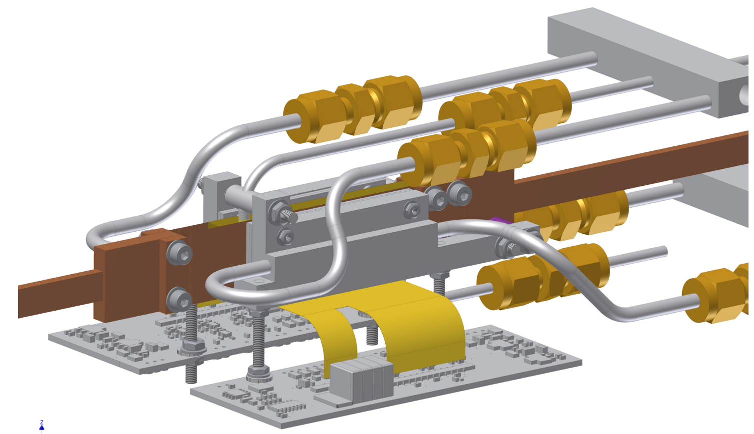
Active shielding

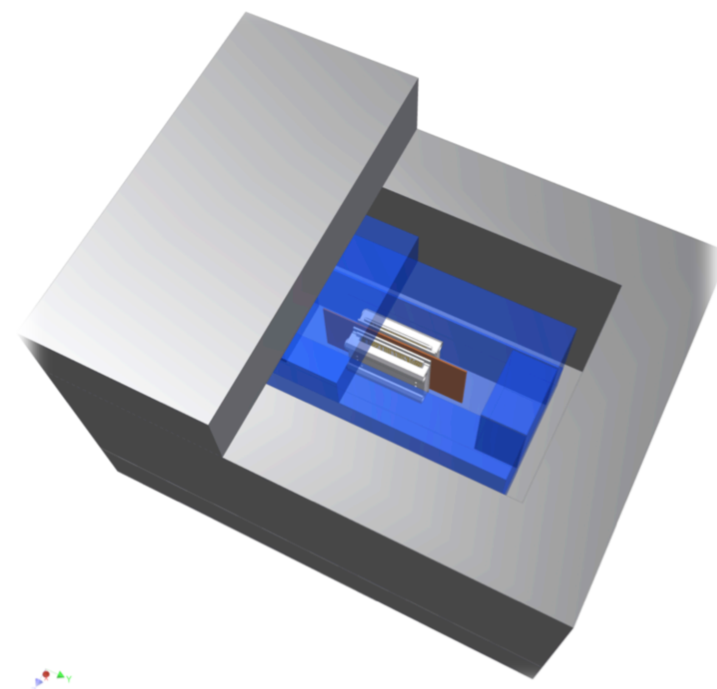
Stefan Meyer Institute

ÖAW Austrian Academy of Sciences

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

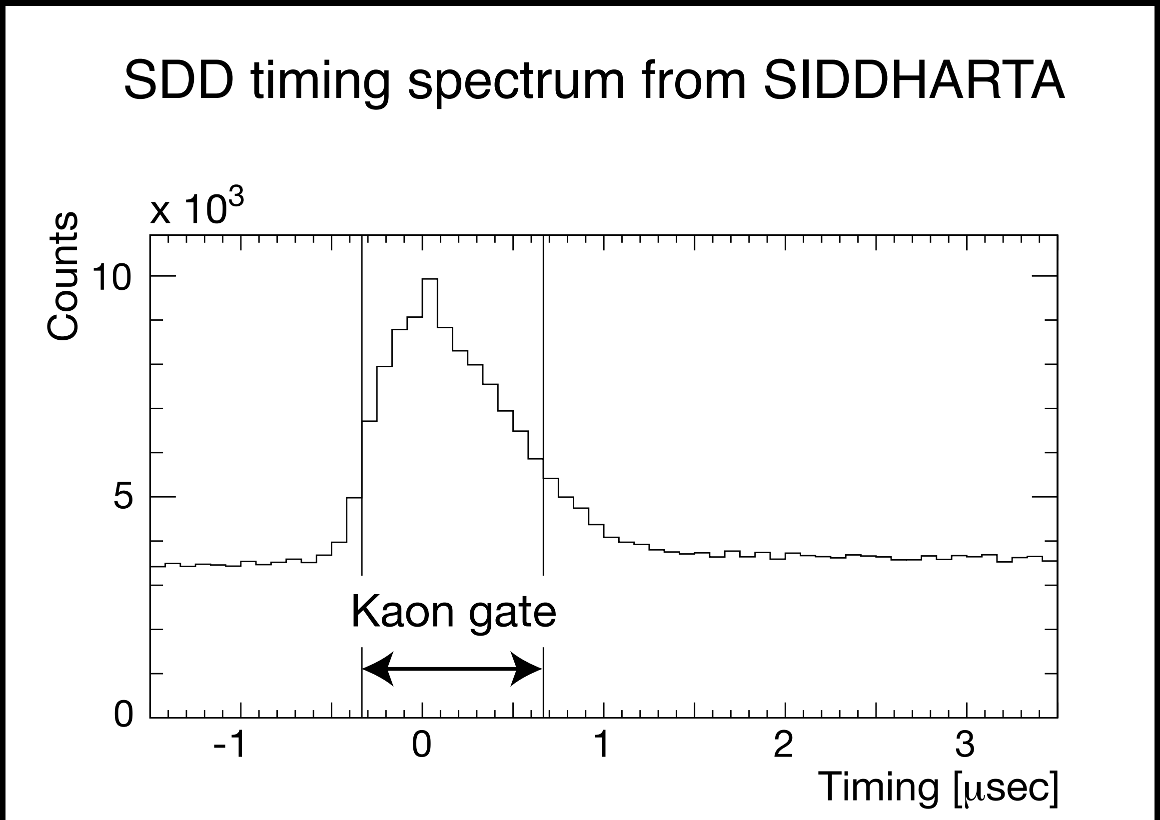




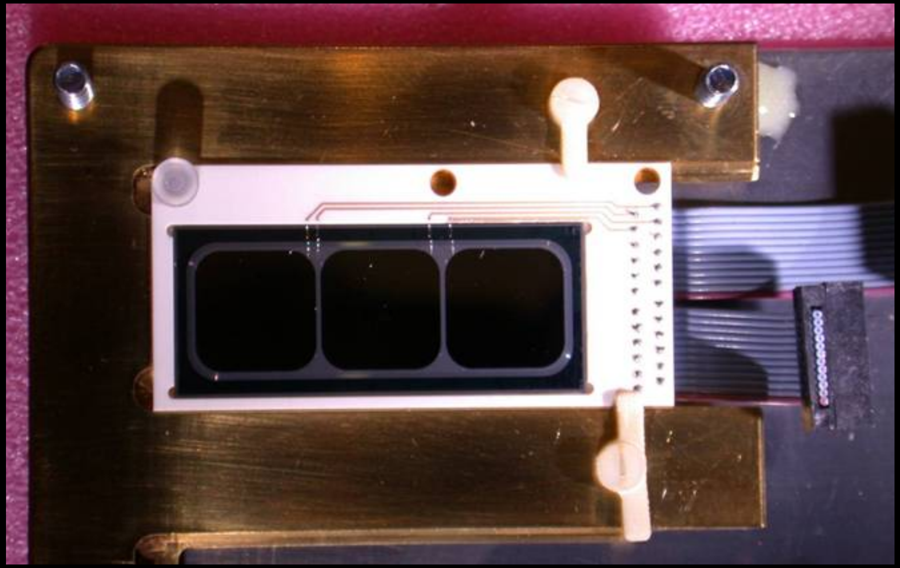


J. Marton 2013 TAUP

Silicon Drift Detectors with timing capability

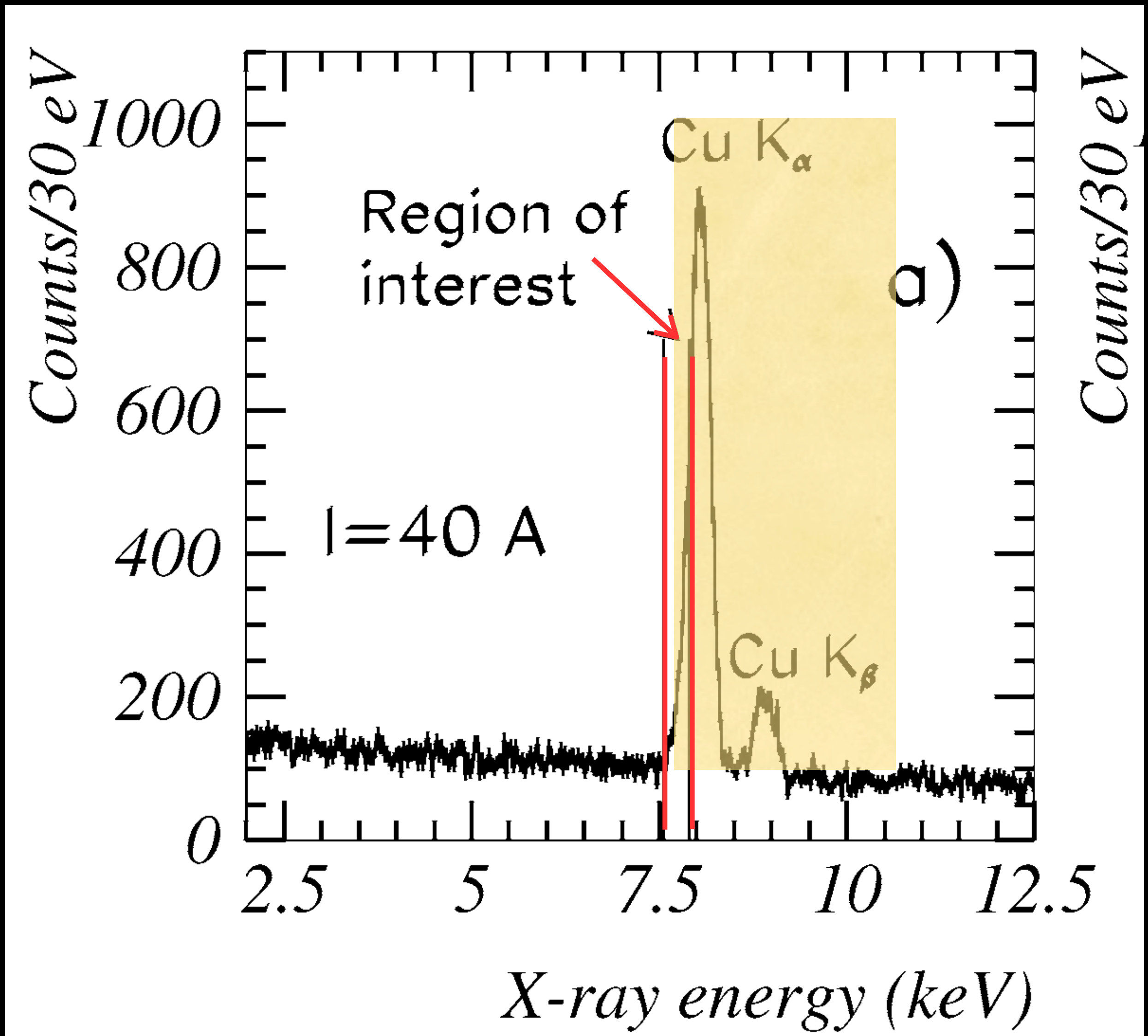


M. Bazzi, Physics Letters B 704 (2011) 113–117



SDD used in SIDDHARTA
measuring kaonic atom X-rays

VIP CCD energy spectrum

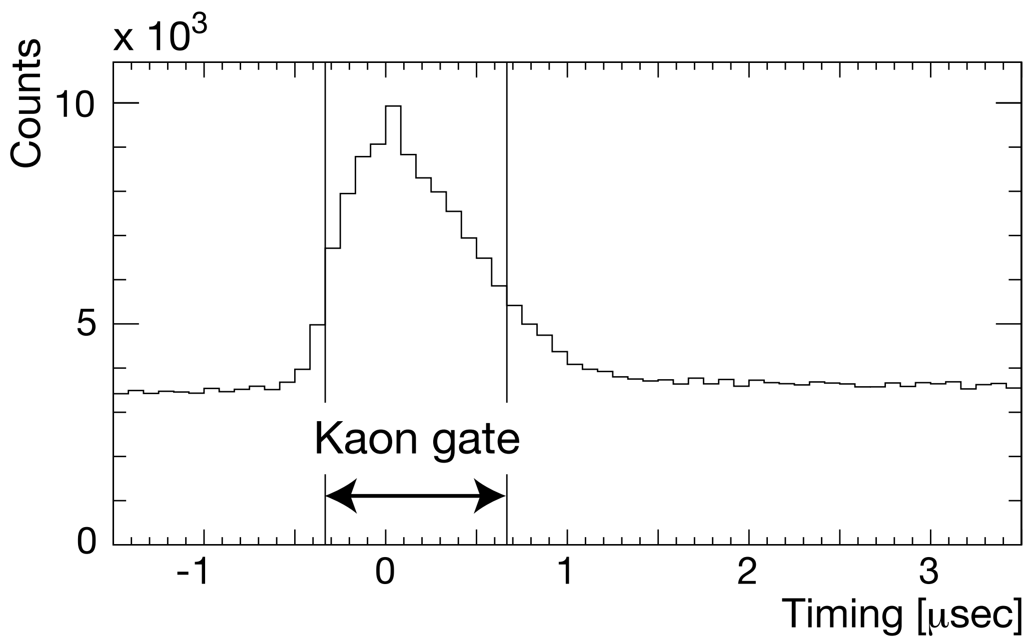


S. Bartalucci, et. al, Physics Letters B **641**, 18 (2006).

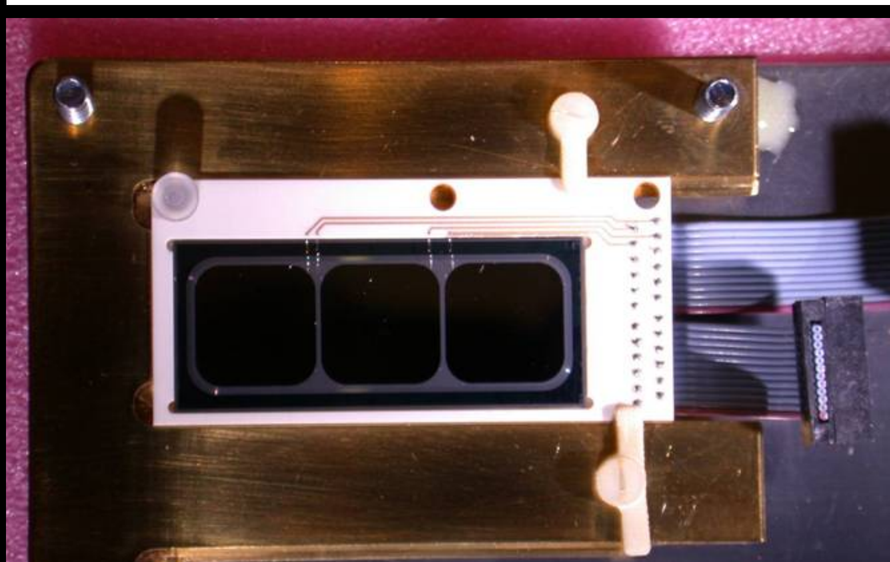
normal fluorescence X-rays from copper are background
origin from excited copper atoms

Silicon Drift Detectors with timing capability

SDD timing spectrum from SIDDHARTA

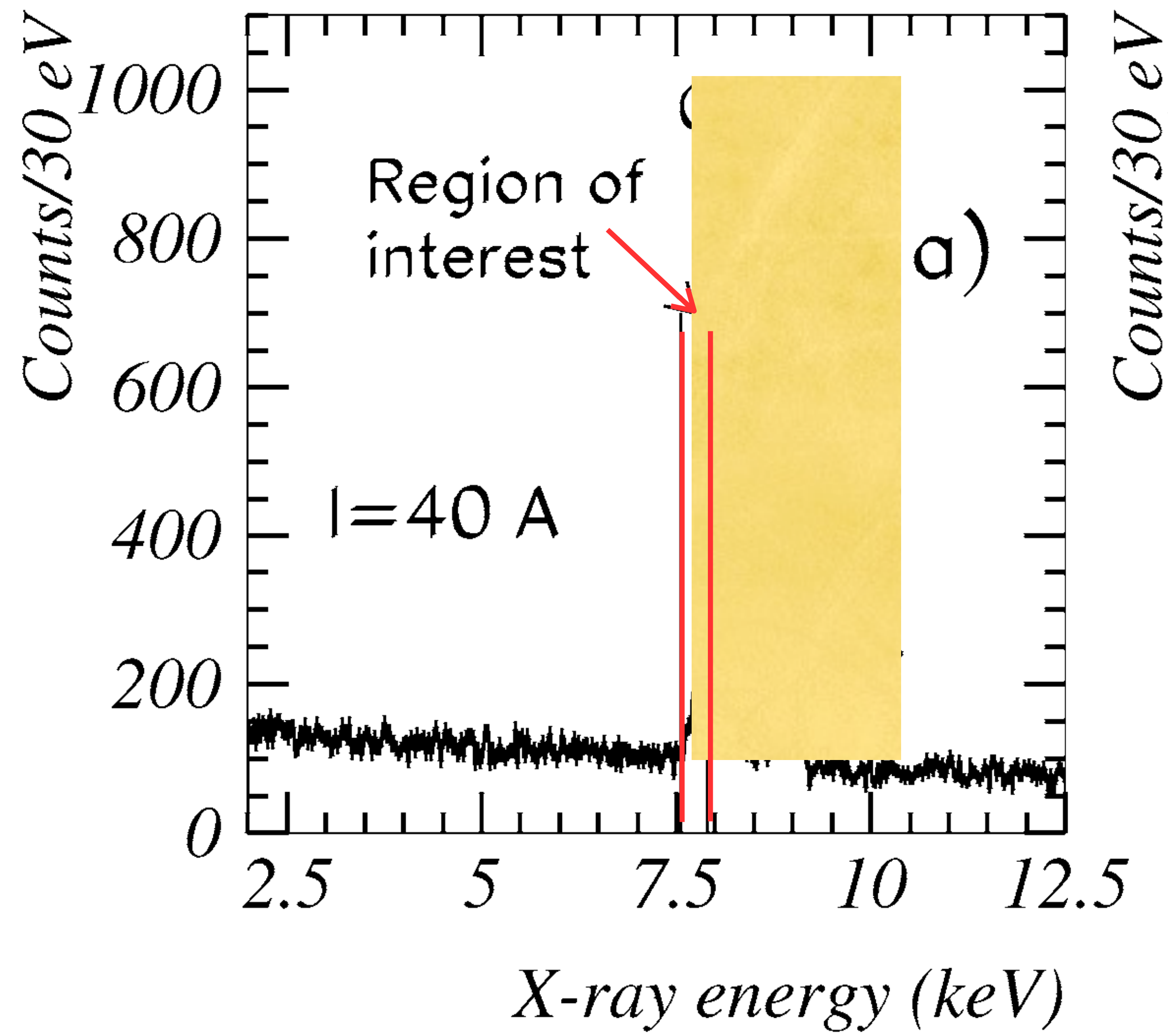


M. Bazzi, Physics Letters B 704 (2011) 113–117



SDD used in SIDDHARTA measuring kaonic atom X-rays

VIP CCD energy spectrum



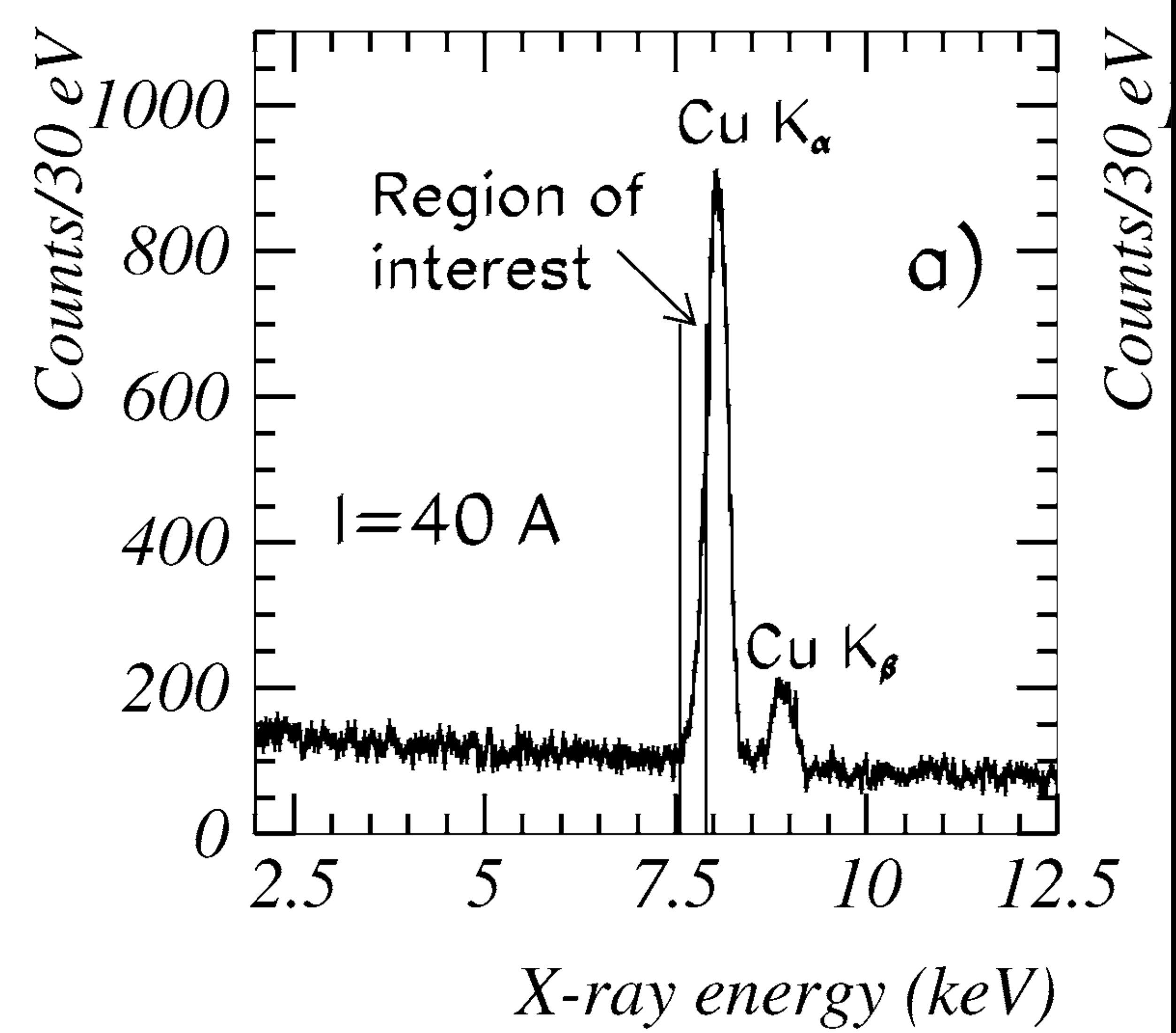
S. Bartalucci, et. al, Physics Letters B **641**, 18 (2006).

normal fluorescence X-rays from copper are background, origin from excited copper atoms

→ can be excluded using time information

CCD to SDD - Energy Resolution

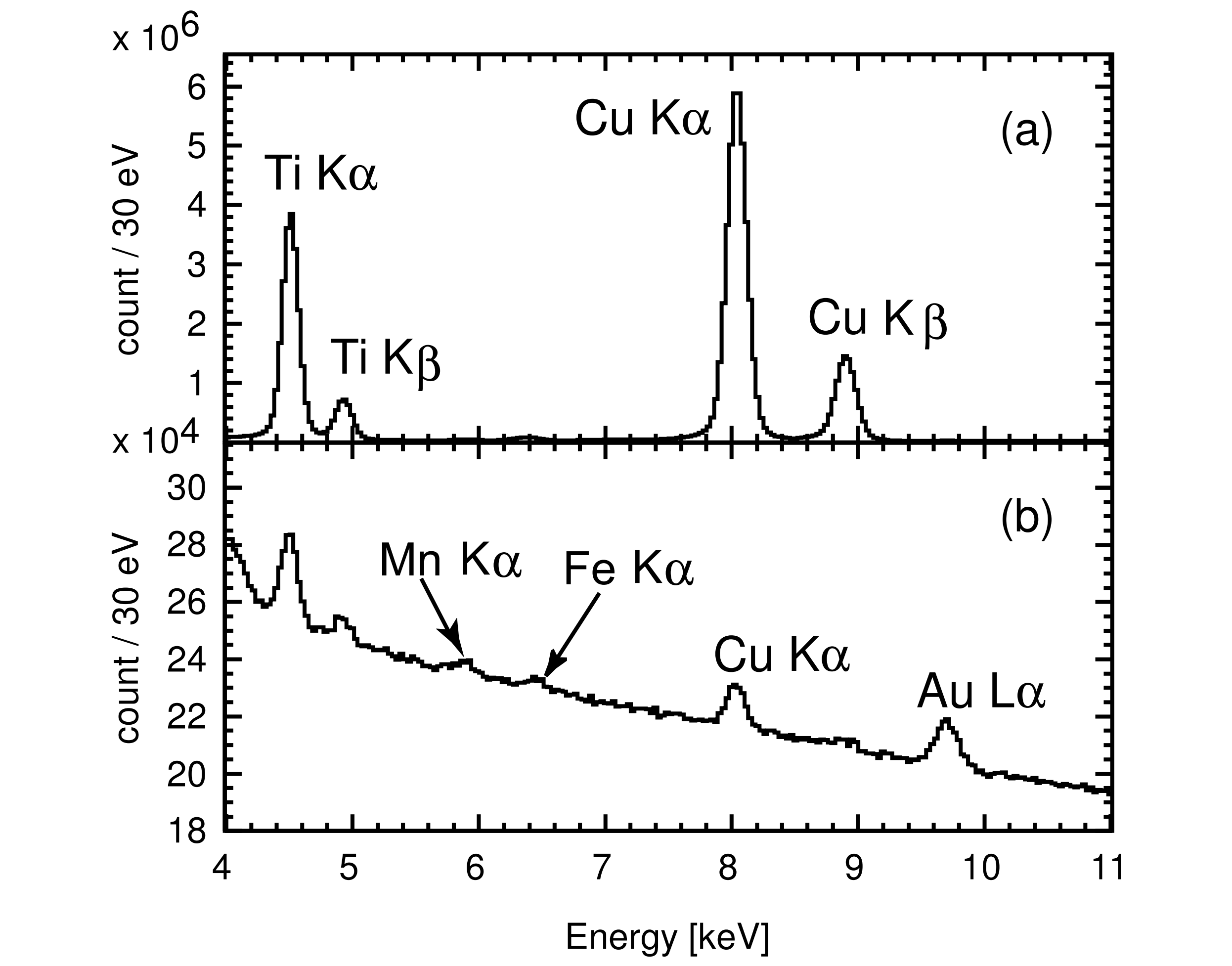
VIP



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

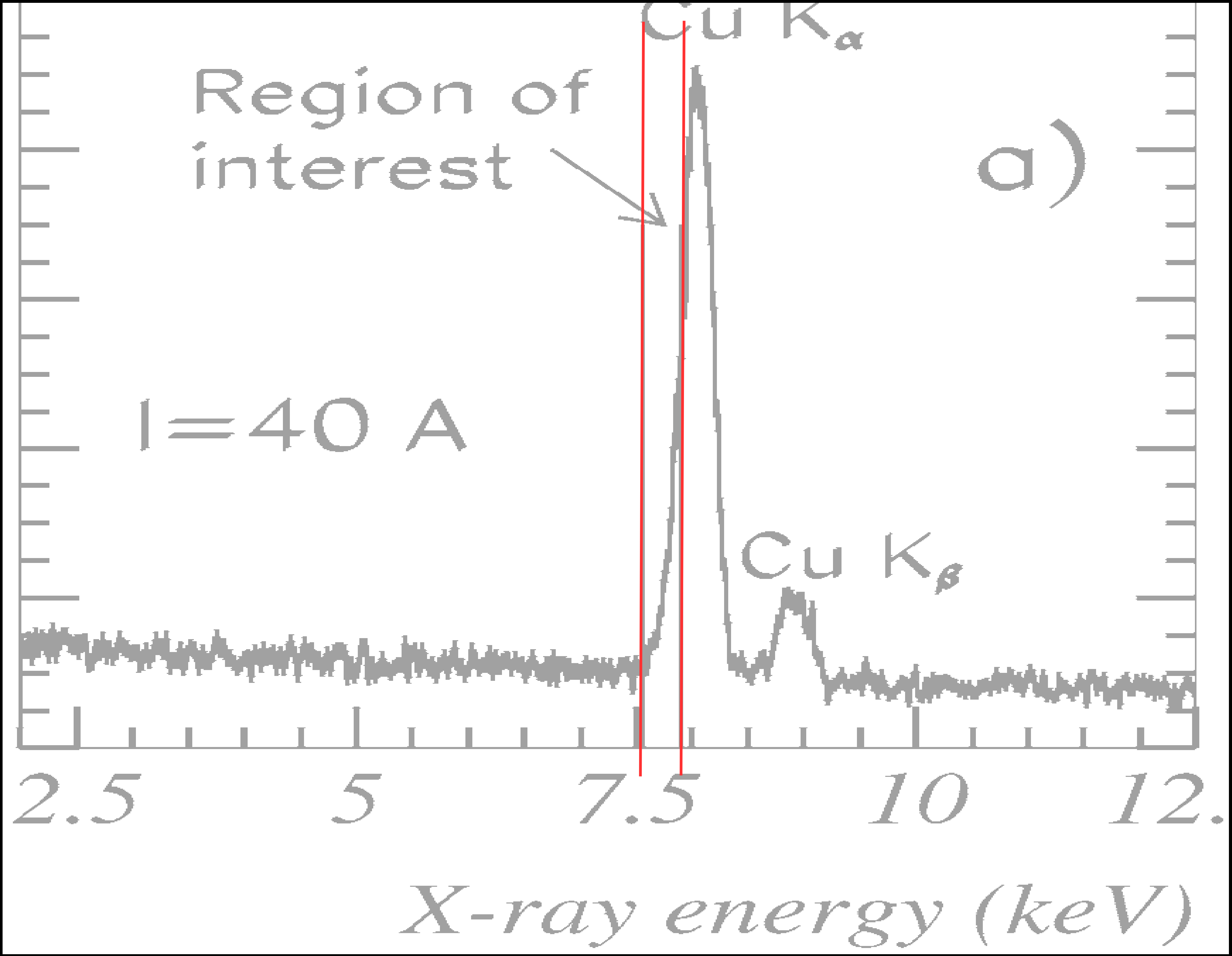
FWHM 340 eV
@ 8 keV

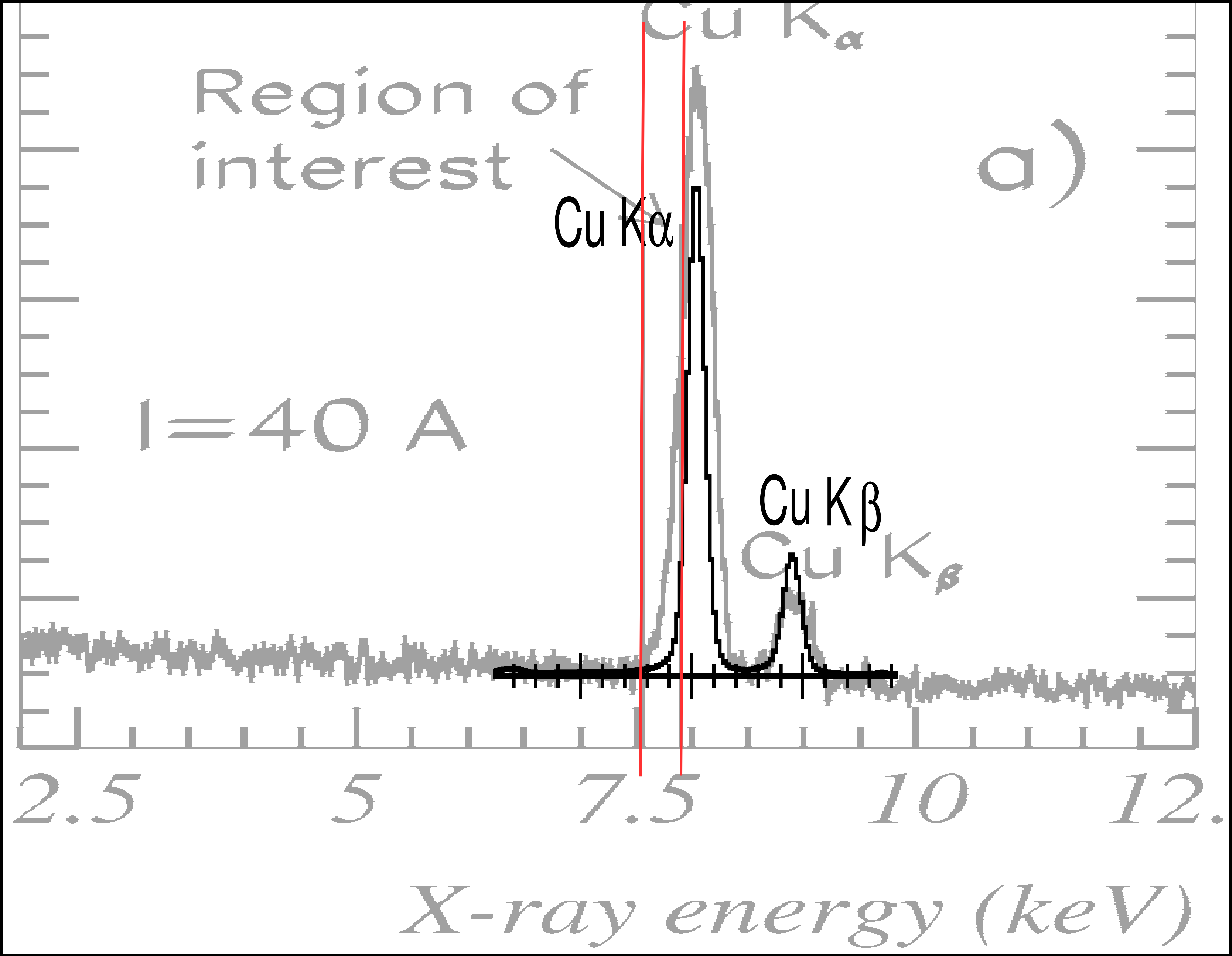
SIDDHARTA



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

FWHM 170 eV
@ 8 keV

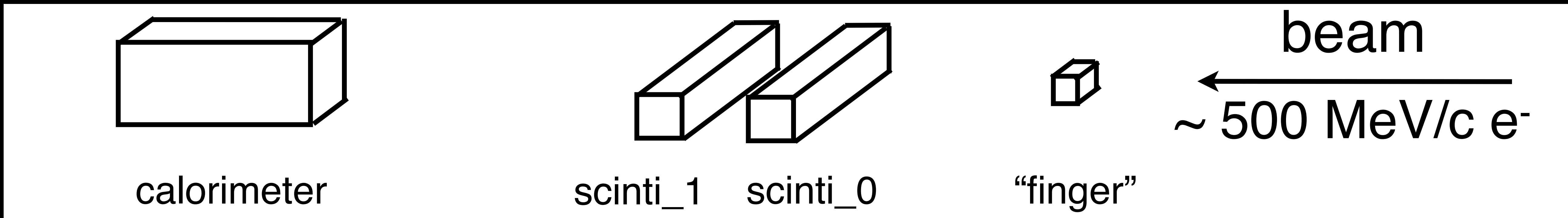

Cu K$_\alpha$
Region of interest
a)
I=40 A
Cu K$_\beta$
2.5
5
7.5
10
12.
X-ray energy (keV)


Cu Kα
Region of interest
a)
Cu Kα
Cu Kβ
Cu Kβ
I=40 A
2.5
5
7.5
10
12.
X-ray energy (keV)

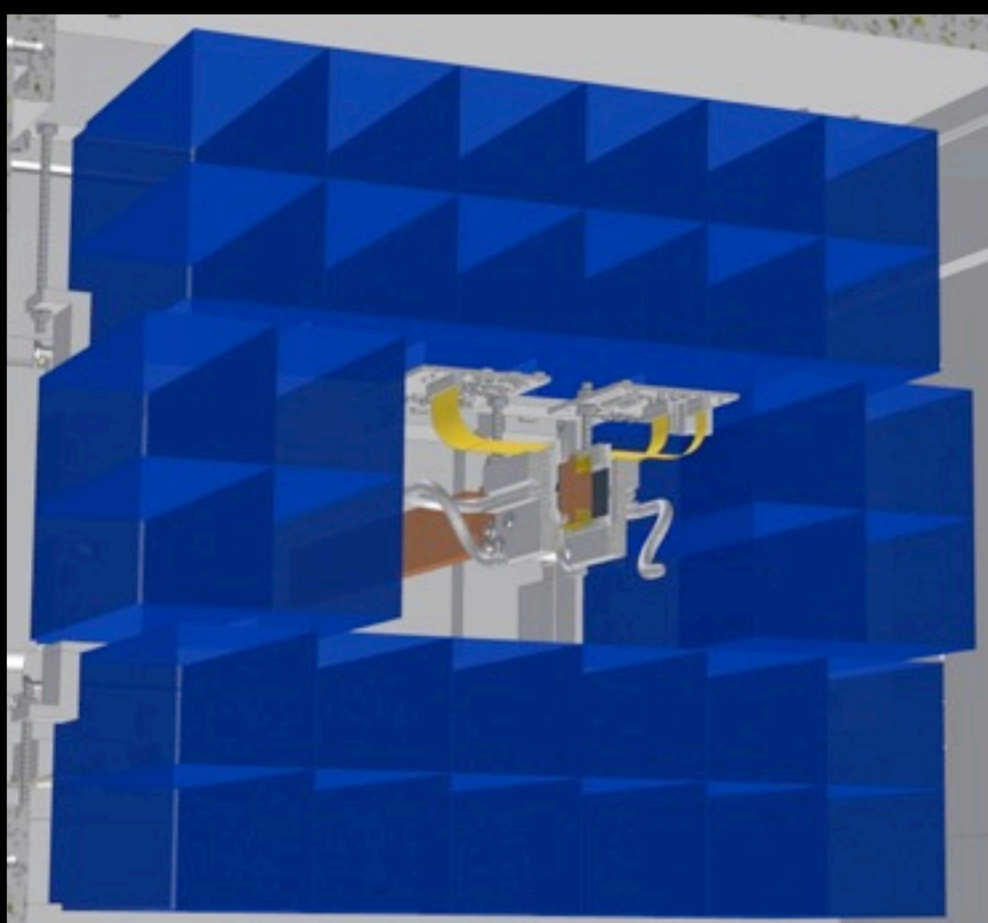
Preparation at LNF

Beam Test Facility test for scintillators

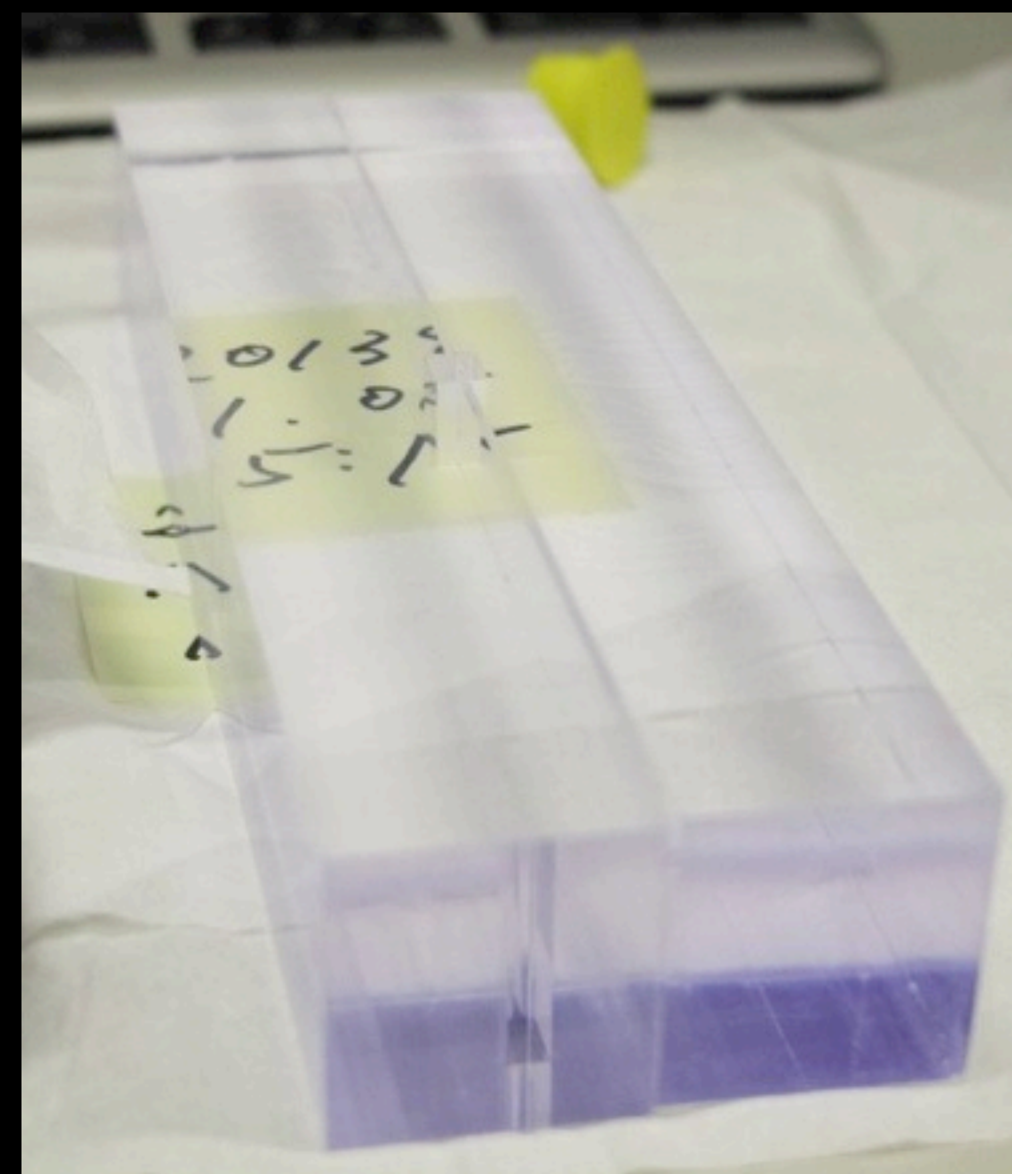
Dec. 2013, LNF



timing performance checked; efficiency better than 97%.

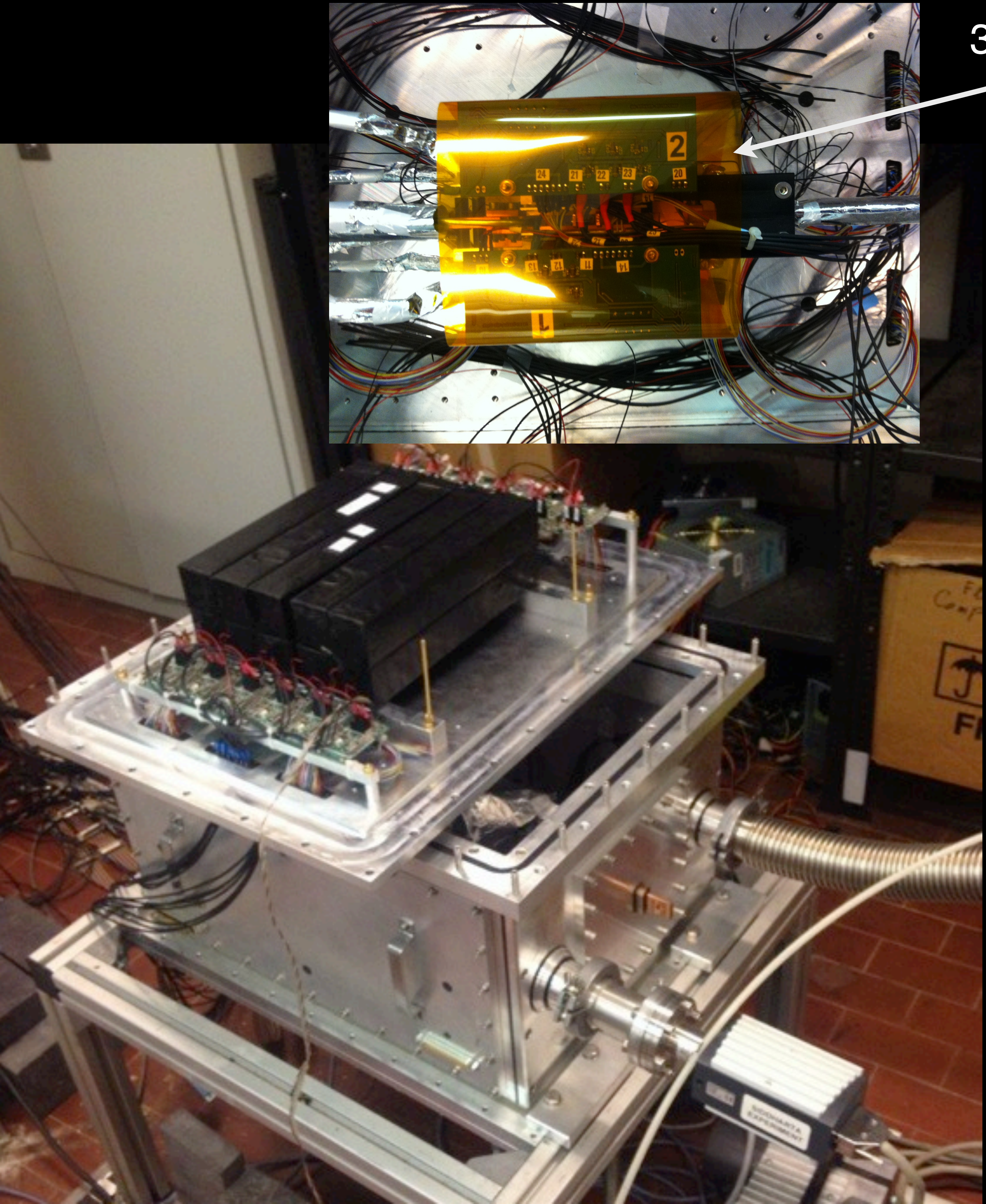


artist cut-away view of VIP-2 setup



two scintillator bars after polishing

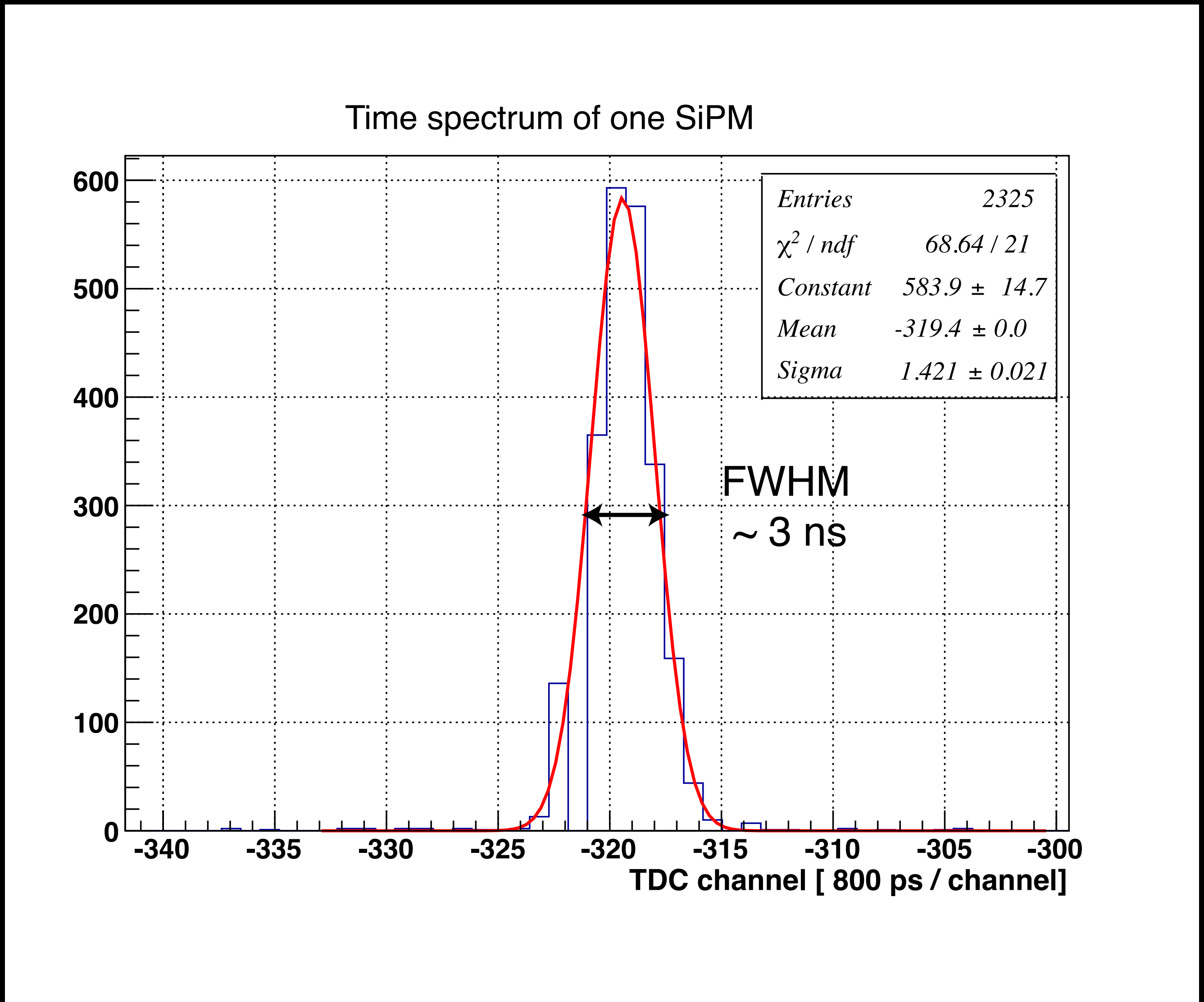
Test setup at LNF

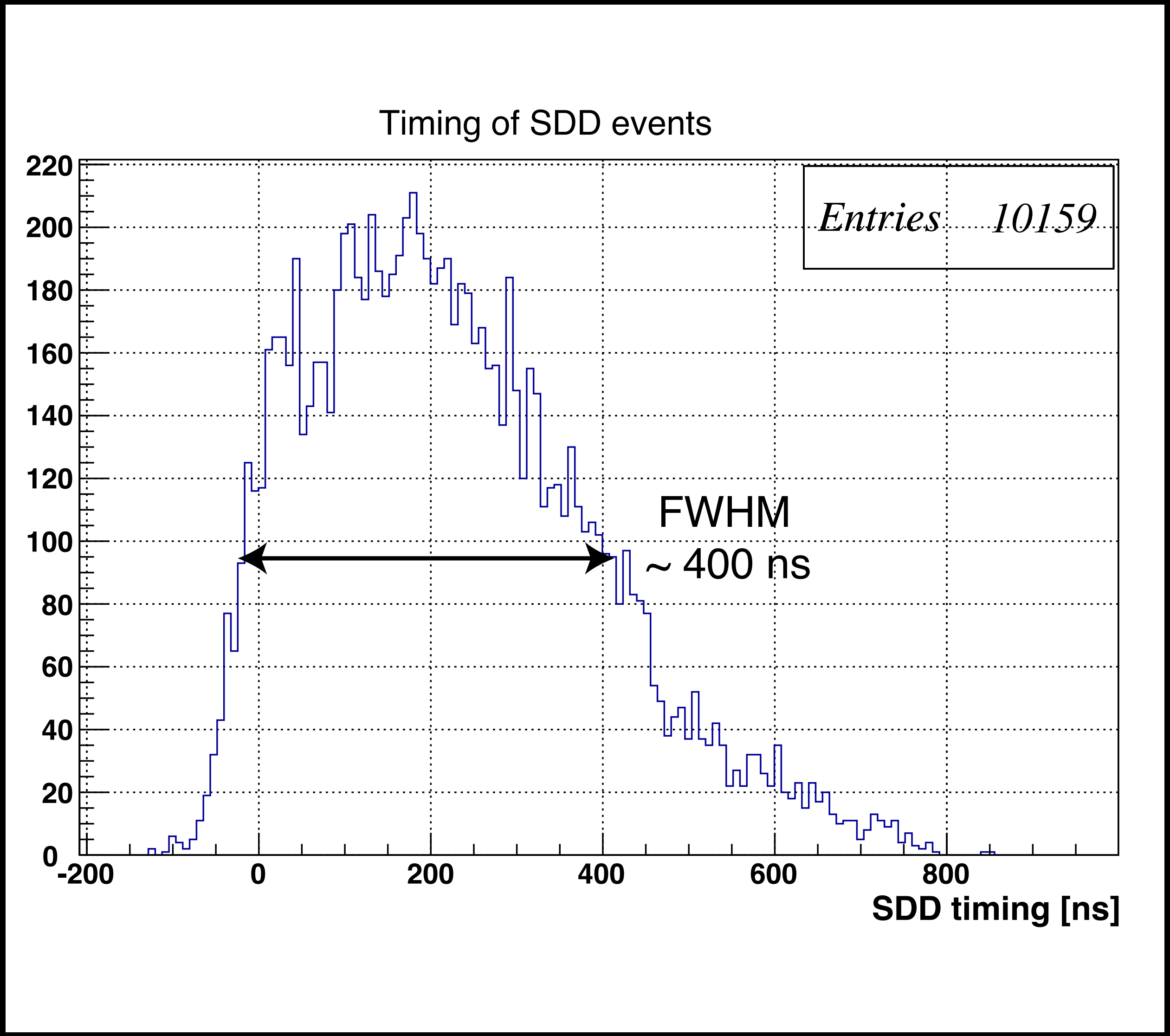


3 x 2 SDDs

Ten scintillator detectors for active shielding, with readout by SiPMs

Detector timing performance





time resolution of scintillator from BTF measurement

time resolution of SDDs from test setup measurement of cosmic rays

VIP-2 improvement factors

Table 2. List of numerical values of the changes in VIP2 in comparison to the VIP features (given in brackets)

Changes in VIP2	value VIP2 (VIP)	expected gain
acceptance	12% (1 %)	12
increase current	100A (50A)	2
reduced length	3 cm (8.8 cm)	1/3
total linear factor		8
energy resolution	170 eV (340 eV)	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

J. Marton, et. al, JoP: Conference Series **447**, (2013)012070.

outlook for VIP-2

- energy calibration and tuning for the SDDs;

- whole system will be ready by the end of 2014;

- final setup to LNGS, data taking will last for two years.

Summary

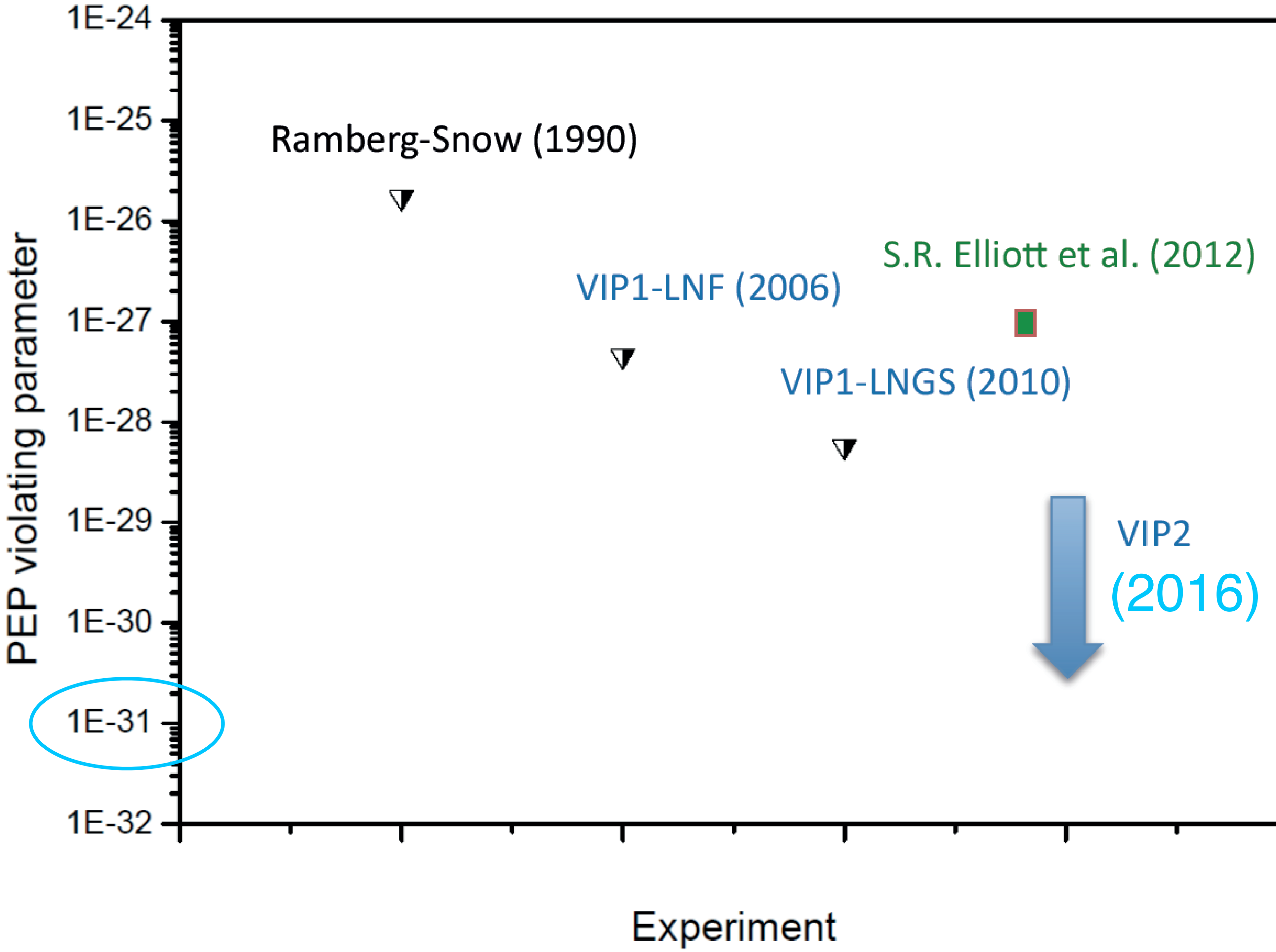
- Pauli Principle, fundamental yet a postulate, open to question, quantitative test by experiments is difficult;

- searching for Pauli-forbidden atomic transitions by supplying "new" electrons to atomic system, started by Ramberg & Snow (RS), is by far the most systematically studied experimental approach;

- VIP experiment used high-precision X-ray spectroscopy, it set the limit with highest sensitivity using RS method;

- VIP-2 aims to improve the sensitivity by two orders of magnitude, a practical goal confirmed by test measurements in Frascati.

Towards VIP-2



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Spare

Calculated "anomalous" transition energies

Transitions for Copper

Transition	Pauli obeying transitions	Pauli violating transitions		Energy difference
	Standard transition Energy [eV]	Energy [eV]	Transition probability velocity [1/s]	$E_{standard}$-E_{VIP} [eV]
$2p_{1/2}$ ==» $1s_{1/2}$ ($K_{\alpha 2}$)	8,047.78	7,728.92	2.6372675E+14	318.86
$2p_{3/2}$==» $1s_{1/2}$ ($K_{\alpha 1}$)	8,027.83	7,746.73	2.5690970E+14	279.84
$3p_{1/2}$ ==» $1s_{1/2}$ ($K_{\beta 2}$)	8,905.41	8,529.54	2.7657639E+13	375.87
$3p_{3/2}$==» $1s_{1/2}$ ($K_{\beta 1}$)	8,905.41	8,531.69	2.6737747E+13	373.72
$3d_{3/2}$==»$2p_{3/2}$ ($L_{\alpha 2}$)	929.70	822.84	5.9864102E+07	106.86
$3d_{5/2}$==»$2p_{3/2}$ ($L_{\alpha 1}$)	929.70	822.83	3.4922759E+08	106.87
$3d_{3/2}$==»$2p_{1/2}$ ($L_{\beta 1}$)	949.84	841.91	3.0154308E+08	107.93
$3s_{1/2}$==» $2p_{1/2}$	832.10	762.04	3.7036365E+11	70.06
$3s_{1/2}$ ==» $2p_{3/2}$	811.70	742.97	7.8424473E+11	68.73
$3d_{5/2}$ ==» 1s (**D**irect **R**adiative **R**ecombination)	8,977.14	8,570.82	1.2125697E+06	406.32

Kα

Multiconfiguration Dirac-Fock approch

considered:

- relativistic corrections
- lamb shift
- Breit operator
- radiative corrections

Preprint: INFN-13-21/LNF (2013)

http://www.lnf.infn.it/sis/preprint/detail.php?id=5330

Parameter "β" in quon algebra

the β²/2 convention comes from its connection to the *q* parameter of the quon theory by Greenberg and Mohapatra

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

the quon algebra is defined as the convex sum of the fermion and boson algebra as:

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

or in the form:

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

O. W. Greenberg, in *Spin-Statistics Connection and Commutation Relations* (AIP, 2000), pp. 113–127.

Not consistent with local quantum field theory

Interpretation of the experiment results

- capture cross-section (estimated by taking the anomalous electron as muon), cascade processes not clear..

Calculations (Ramberg & Snow)

The number of "new" electrons passing through the Cu conductor:

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

The minimum number of scattering process on the atoms of the copper lattice, per electron, is of order:

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

D ← Length of the copper electrode

μ ← Mean free path of electron in copper

We assume that the capture probability is > 1/10 of the scattering probability.

The X-rays produced in the atomic transitions can be absorbed inside before to reach the detector. Be σ the absorption cross section, the <u>mean absorption length</u> will be:

$$\lambda = \frac{1}{\sigma \rho}$$

If z is the copper thickness, the fraction of visible current to the detector will be λ/z and the expected nuber of X-rays is:

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

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

$$D = 0.025 m \qquad \sigma = 10 m^2 \cdot kg^{-1}$$

$$\mu = 3.9 \cdot 10^{-8} m \qquad z = 1.5 \cdot 10^{-3} m$$

$$\rho = 8.96 \cdot 10^3 kg \cdot m^{-3} \qquad e = 1.6 \cdot 10^{-19} C$$

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

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

SIF - XCIII Congresso Nazionale *Pisa, 24-29 Settembre 2007* 21

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Analysis of VIP with RS method:

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

$$D = 0.088m$$

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

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

$$f_g \approx 0.01$$

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

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

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

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

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

A summary of previous limits

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

Process	Type	Experimental limit	$\frac{1}{2}\beta^2$ limit	
Atomic transitions				
$\beta^- + \mathrm{Pb} \rightarrow \check{\mathrm{Pb}}$	Ia recently created fermions (electrons)		3×10^{-2}	
$e^-_{pp} + \mathrm{Ge} \rightarrow \check{\mathrm{Ge}}$	Ia		1.4×10^{-3}	
$e^-_I + \mathrm{Cu} \rightarrow \check{\mathrm{Cu}}$	II distant fermions (electrons)		1.7×10^{-26}	
$e^-_I + \mathrm{Cu} \rightarrow \check{\mathrm{Cu}}$	II		4.5×10^{-28}	VIP results
$e^-_I + \mathrm{Cu} \rightarrow \check{\mathrm{Cu}}$	II		6.0×10^{-29}	VIP results
$e^-_I + \mathrm{Pb} \rightarrow \check{\mathrm{Pb}}$	II		1.5×10^{-27}	S. R. Elliott et al., Found Phys (2012) 42:1015–1030
$e^-_f + \mathrm{Pb} \rightarrow \check{\mathrm{Pb}}$	IIa		2.6×10^{-39}	
$\mathrm{I} \rightarrow \check{\mathrm{I}} + \text{X-ray}$	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}	
Nuclear transitions	Stable system transition			
${}^{12}\mathrm{C} \rightarrow {}^{12}\tilde{\mathrm{C}} + \gamma$	III	$\tau > 6 \times 10^{27}$ y	1.7×10^{-44}	
${}^{12}\mathrm{C} \rightarrow {}^{12}\tilde{\mathrm{C}} + \gamma$	III	$\tau > 4.2 \times 10^{24}$ y		
${}^{12}\mathrm{C} \rightarrow {}^{12}\tilde{\mathrm{C}} + \gamma$	III	$\tau > 5.0 \times 10^{31}$ y	2.2×10^{-57}	BOREXINO
${}^{12}\mathrm{C} \rightarrow {}^{11}\tilde{\mathrm{B}} + p$	III	$\tau > 8.9 \times 10^{29}$ y	7.4×10^{-60}	Bellini, G., et al. (2010). Phys. Rev. C, 81(3), 034317

Reines, F., & Sobel, H. W. (1974). Phys. Rev. Lett., 32, 954–954. doi:10.1103/PhysRevLett.32.954
Logan, B. A., & Ljubicic, A. (1979). Physical Review C, 20, 1957–1958. doi:10.1103/PhysRevC.20.1957

Symmetrization Principle

a Super-Selection Rule

"The states of a system containing N identical particles are necessarily either all symmetrical or all anti-symmetrical with respect to permutations of the N particles."

The symmetry type of a state of identical particles is absolutely preserved. Hamiltonian for identical particles must be totally symmetric in their coordinates and thus the symmetry type of the states is conserved by the super-selection rule.

Transitions are forbidden between

states which contain any number of bosons and fermions and at most one particle which is neither a boson nor a fermion

and

state which have more than one non-Bose or non-Fermi particle,

even when the number of particles is not conserved.

Hamiltonian forbids transitions between states of many identical particles in different representation of the permutation group. - Greenberg 1989

Messiah, A., & Greenberg, O. (1964). Physical Review, 136(1B), B248–B267. doi:10.1103/PhysRev.136.B248

Theories of Violation of Statistics

O. W. Greenberg, in *Spin-Statistics Connection and Commutation Relations* (AIP, 2000), pp. 113–127.

- intermediate statistics — G. Gentile, Nuovo Cimento **17**, 493 (1940).
- parastatistics — H. Green, Phys. Rev **90**, 270 (1953).
  (generalized Fermi and Bose statistics)
  parons (hindered parafermions) — O. Greenberg and R. Mohapatra, Phys. Rev. Lett. **59**, 2507 (1987).

- "quons" quon algebra — O. W. Greenberg, in *Spin-Statistics Connection and Commutation Relations* (AIP, 2000), pp. 113–127.

  Not consistent with local quantum field theory

The Igntiev-Kuzmin model (Trilinear model)

- Commutation relations with number operator hold;
- Examined to detail of a perturbed Hamiltonian which includes an explicit violation of the exclusion principle and from here one calculates a transition probability per unit time $W(1 \rightarrow 2)$, which obviously depends of the violation parameter β.