Searches for the Violation of Pauli Exclusion Principle at LNGS

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On behalf of the **VIP-2** collaboration

09th, Sep., 2015
TAUP2015, Torino

Overview

- Experimental *searches* for possible PEP violation,
- Dedicated VIP experiment and result

VIP-2 experiment

- upgrade in VIP-2
- preparation status

Experimental searches for violation of PEP

Search for PEP forbidden <u>states</u>:

nuclear, atomic.

AMS (Accelerator mass spectroscopy)

Search for PEP forbidden <u>transitions</u>:

By-product of experiments in Gran Sasso

BOREXINO

low energy neutrino spectroscopy,
^{7}Be solar neutrino search

DAMA

dark matter search

PEP-forbidden nuclear transitions:

$$^{12}C \rightarrow {}^{11}\tilde{B} + p$$

Bellini, G., et al. (2010). Phys. Rev. C, 81(3), 034317

Atomic transitions:

$$I \rightarrow I + \gamma$$

R Bernabei, et. al., 2010 J. Phys.: Conf. Ser. 202 012039

Pauli Exclusion Principle - in its original presentation

“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. ”

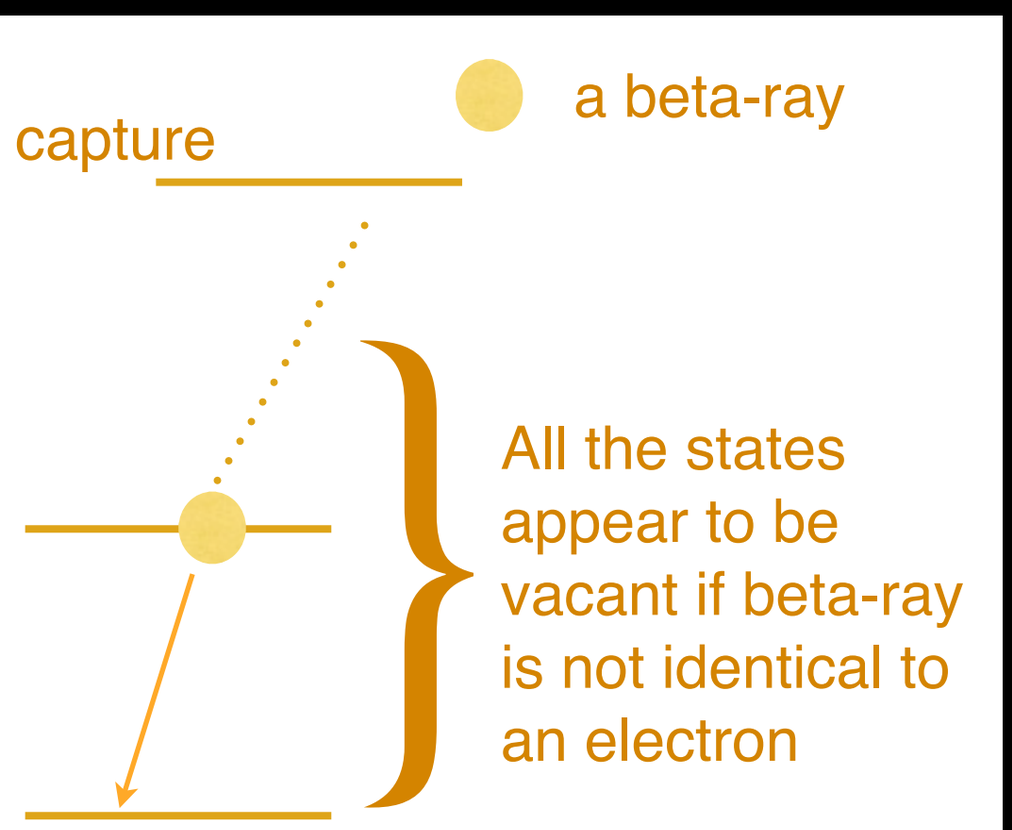
W. Pauli, Zeitschrift für Physik 31(1925) 765.

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}***



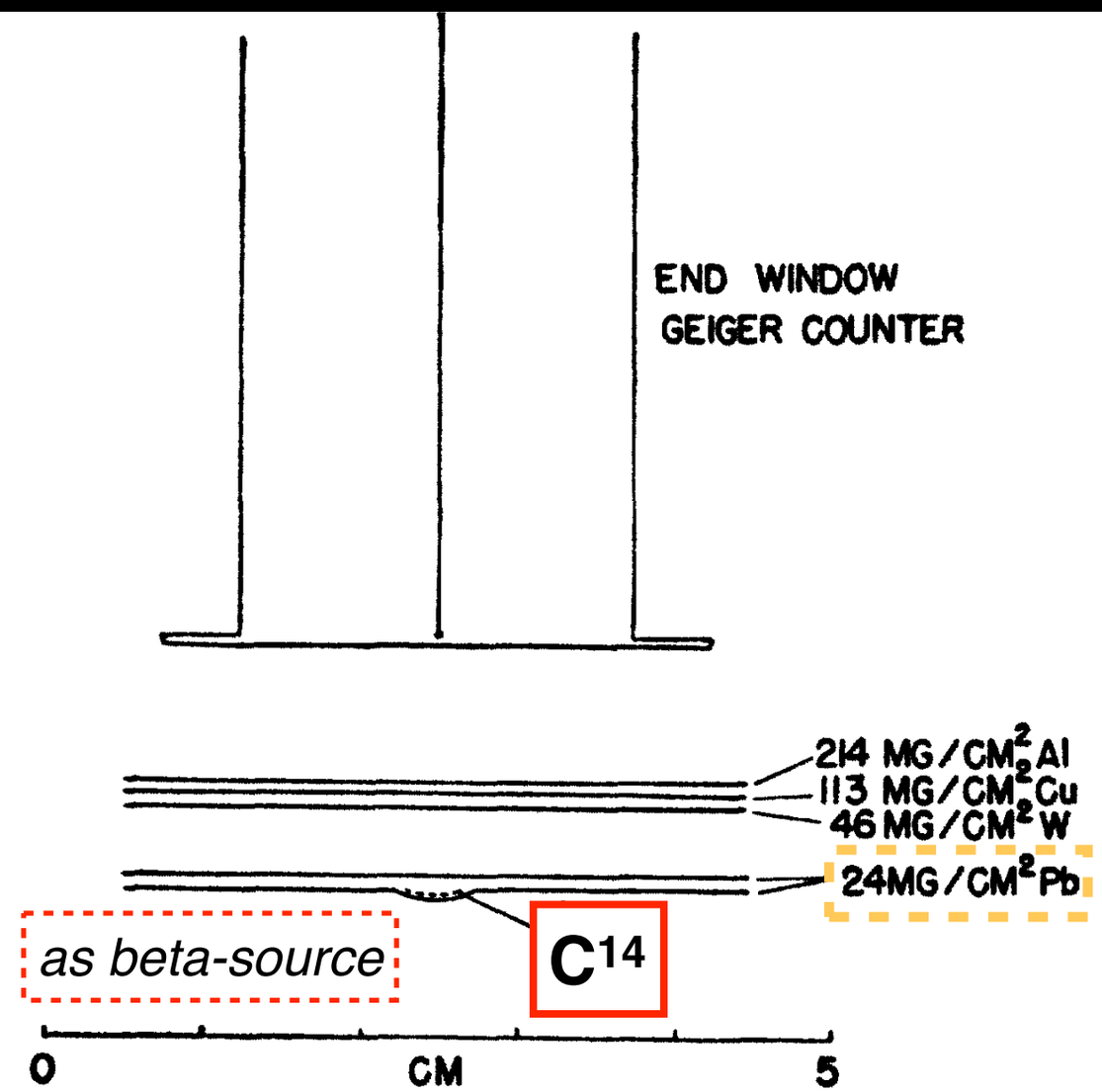
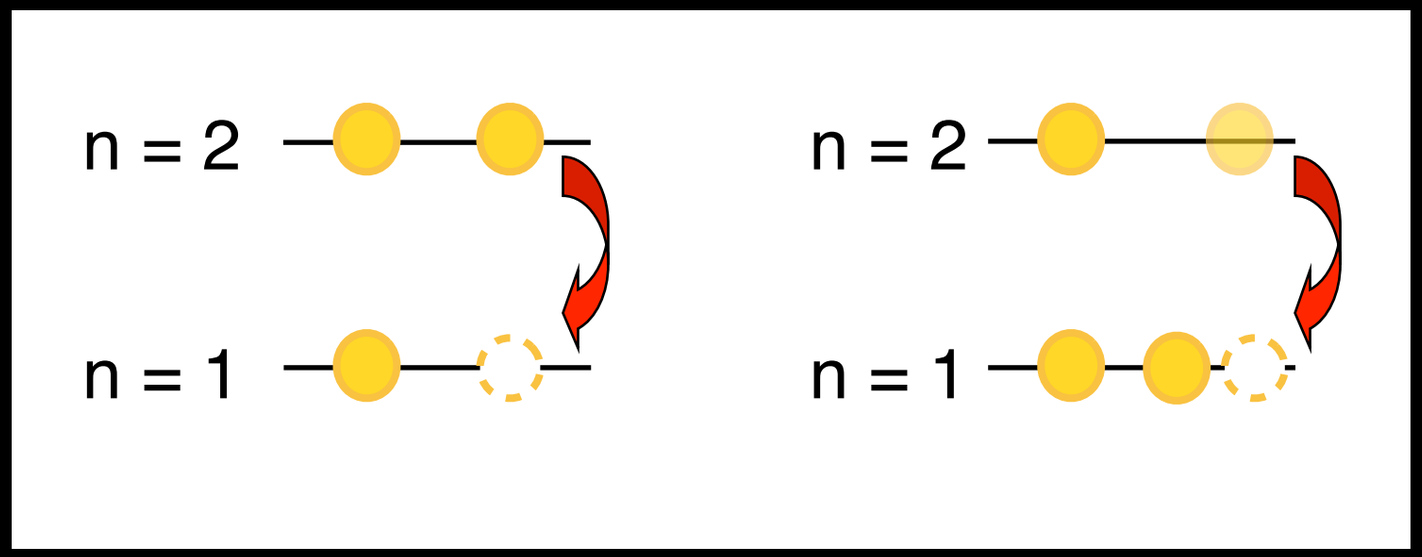


FIG. 1. Arrangement used in search for photons from beta-rays stopped in lead.

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

PEP forbidden X-ray transitions

a most intuitive picture:



Normal 2p→1s transition

<u>8.05 keV for Cu</u>

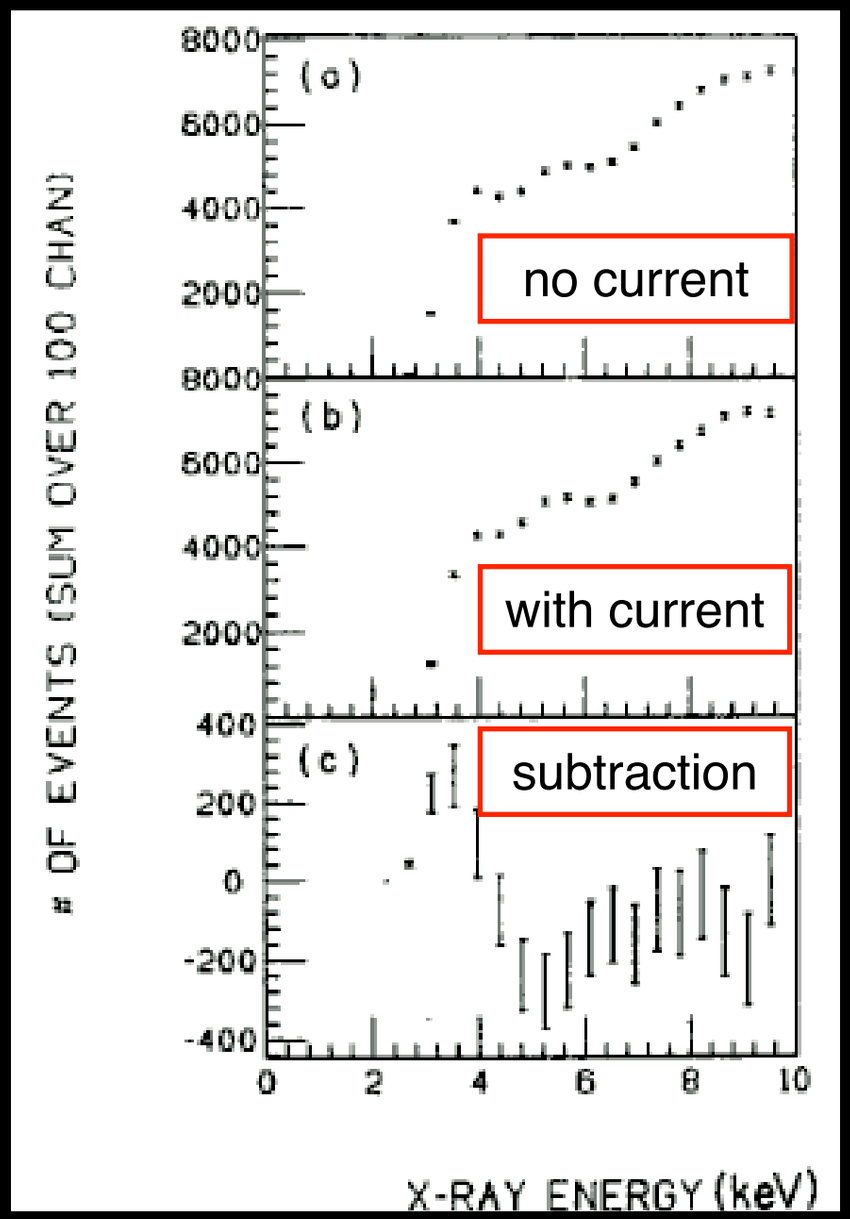
2p→1s transition violating Pauli Principle

<u>~ 7.7 keV for Cu</u>

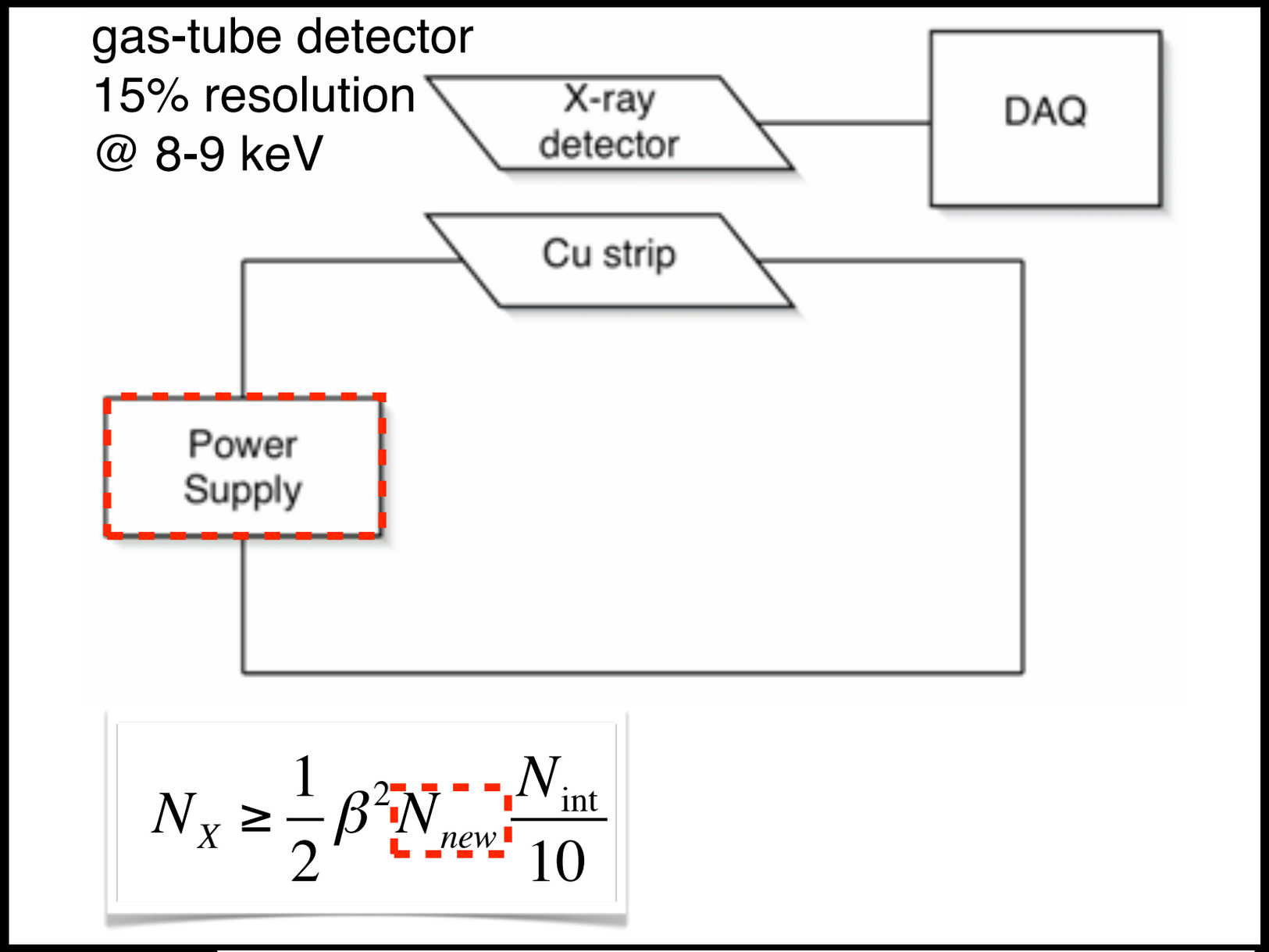
anomalous transition X-rays from atomic states

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



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

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

The parameter "β"

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

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

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 $|1\rangle \rightarrow |2\rangle$. It is very small and for β→0 we can have the Fermi - Dirac statistic again.

The VIP (**VI**olation of the **P**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

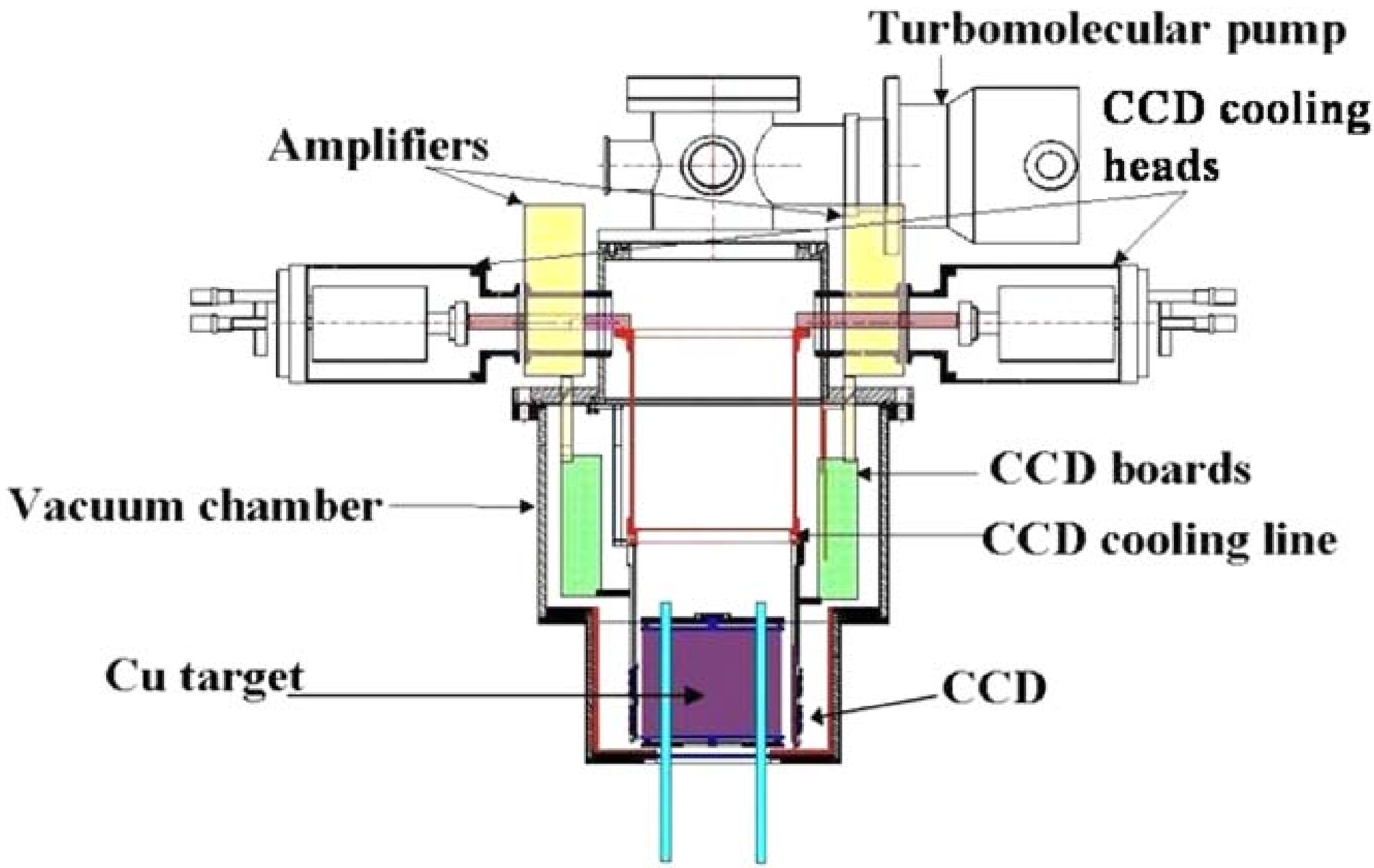
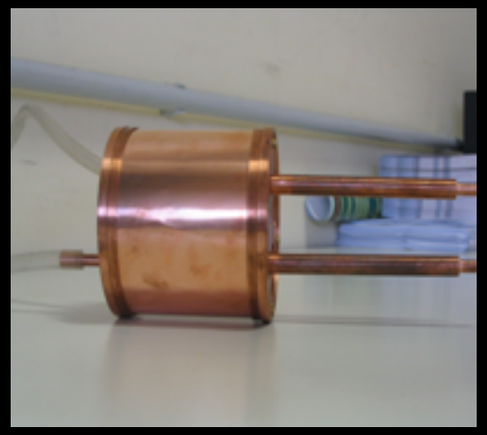


Fig. 1. The VIP setup. All elements at the setup are identified in the figure.

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

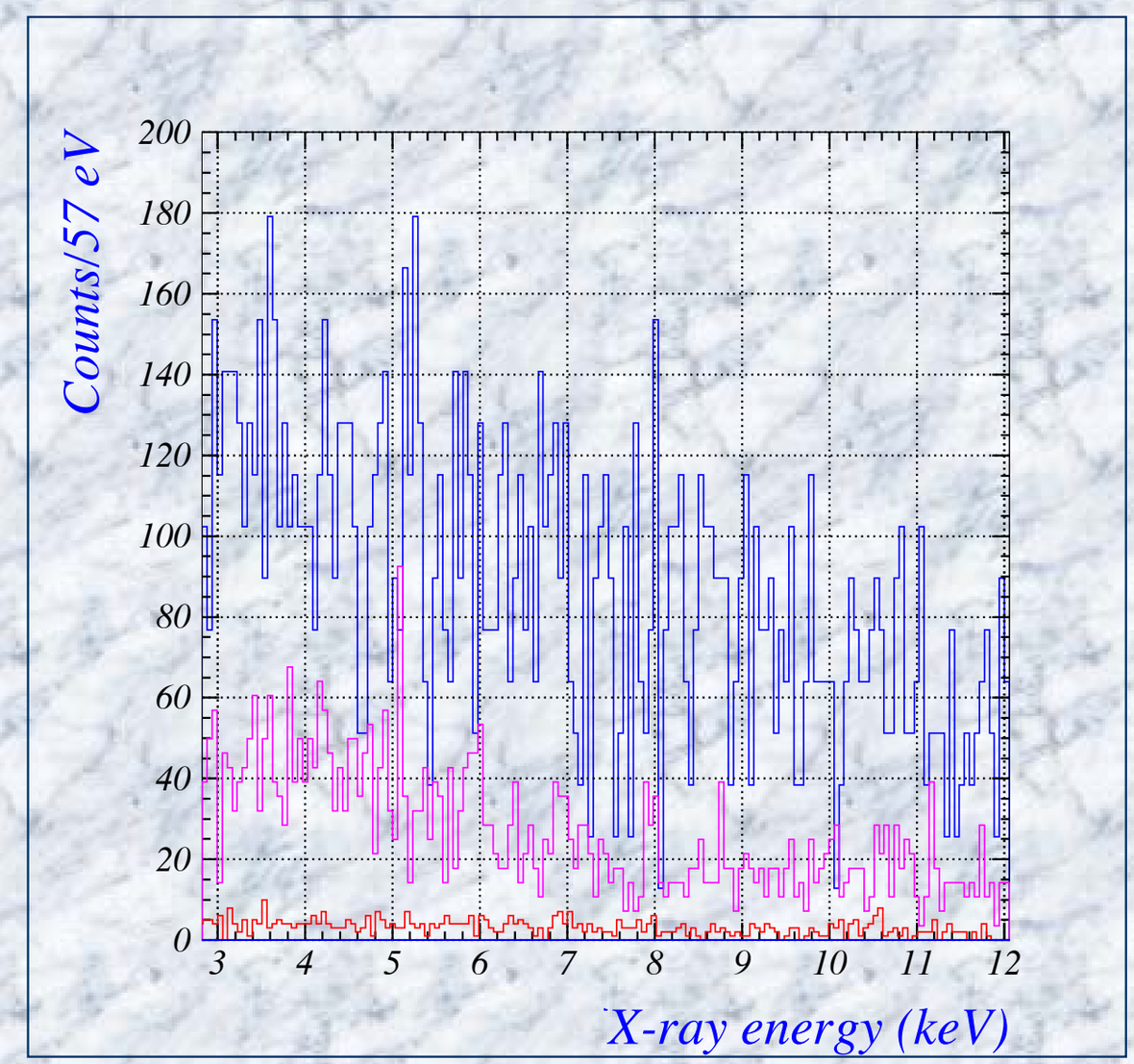
Experiment setup - 2

Cu target



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

w/wo current measurements, same time span

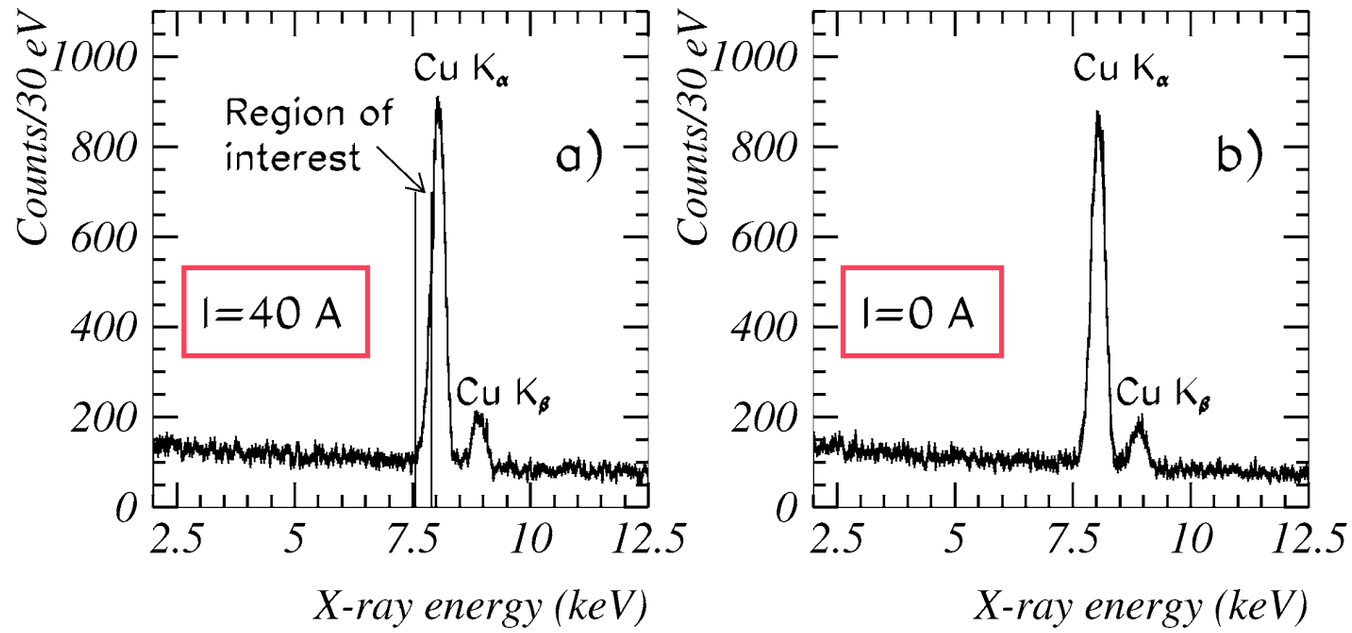
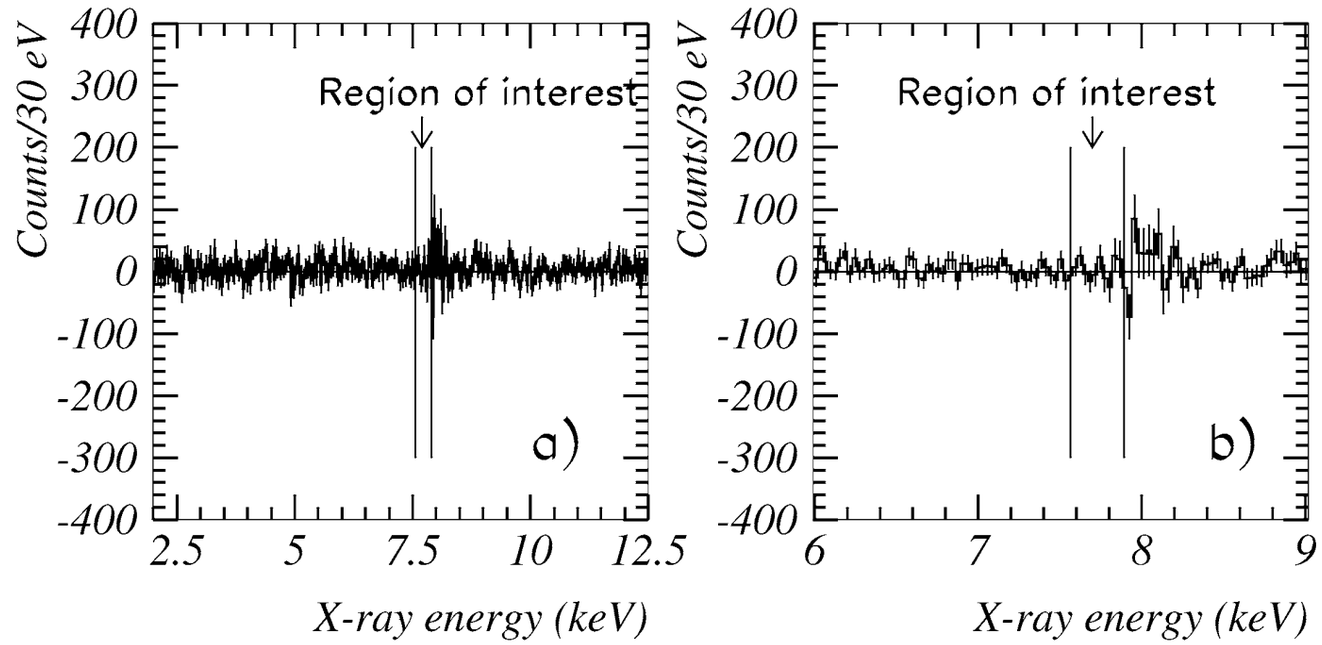


Fig. 2. Energy spectra for the VIP measurements: (a) with current ($I = 40$ A); (b) without current ($I = 0$).

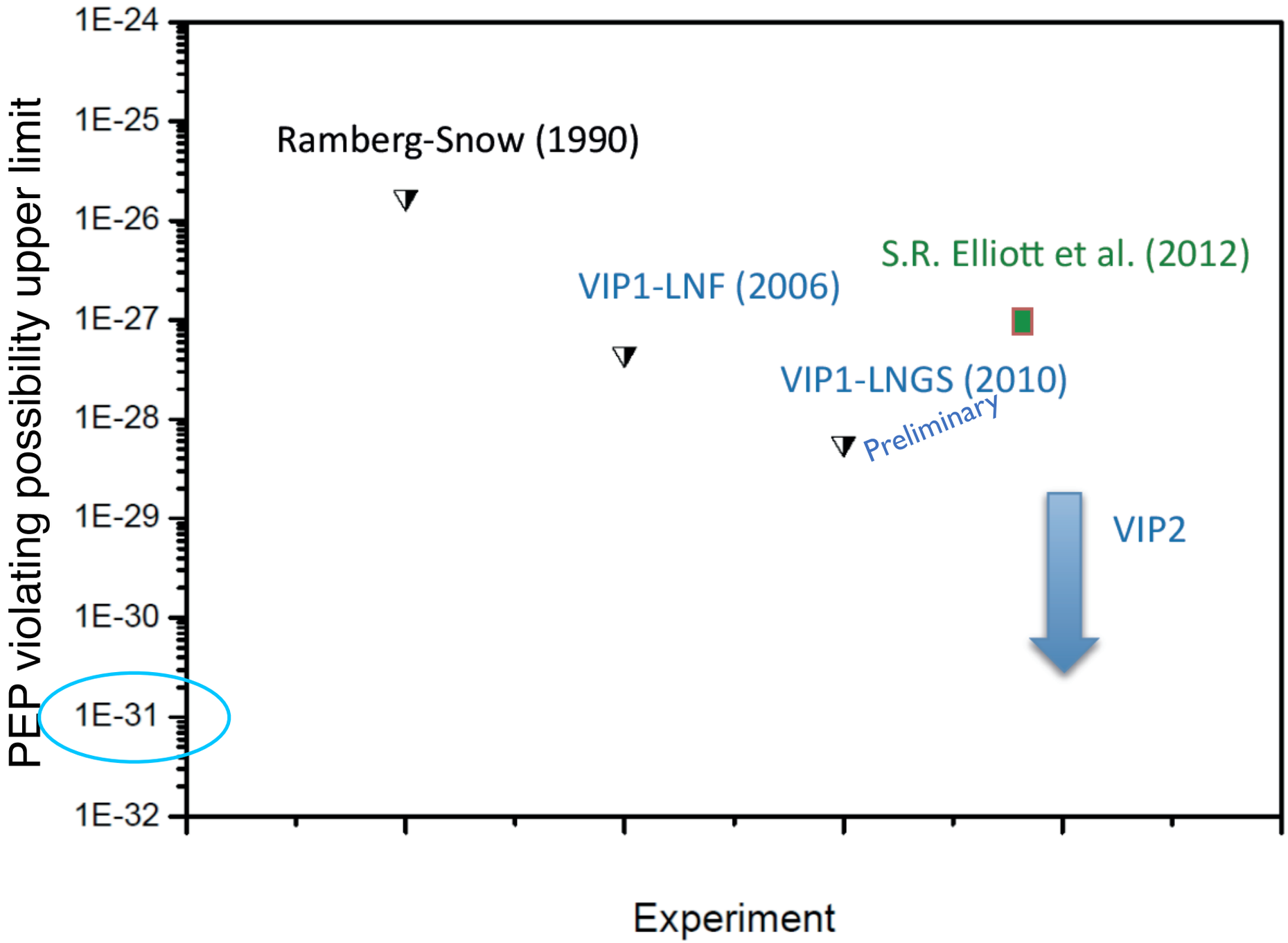
subtraction at ROI gives :
- 21 ± **73** events



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

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

A summary of previous limits and VIP-2 objective



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

The VIP-2 Collaboration

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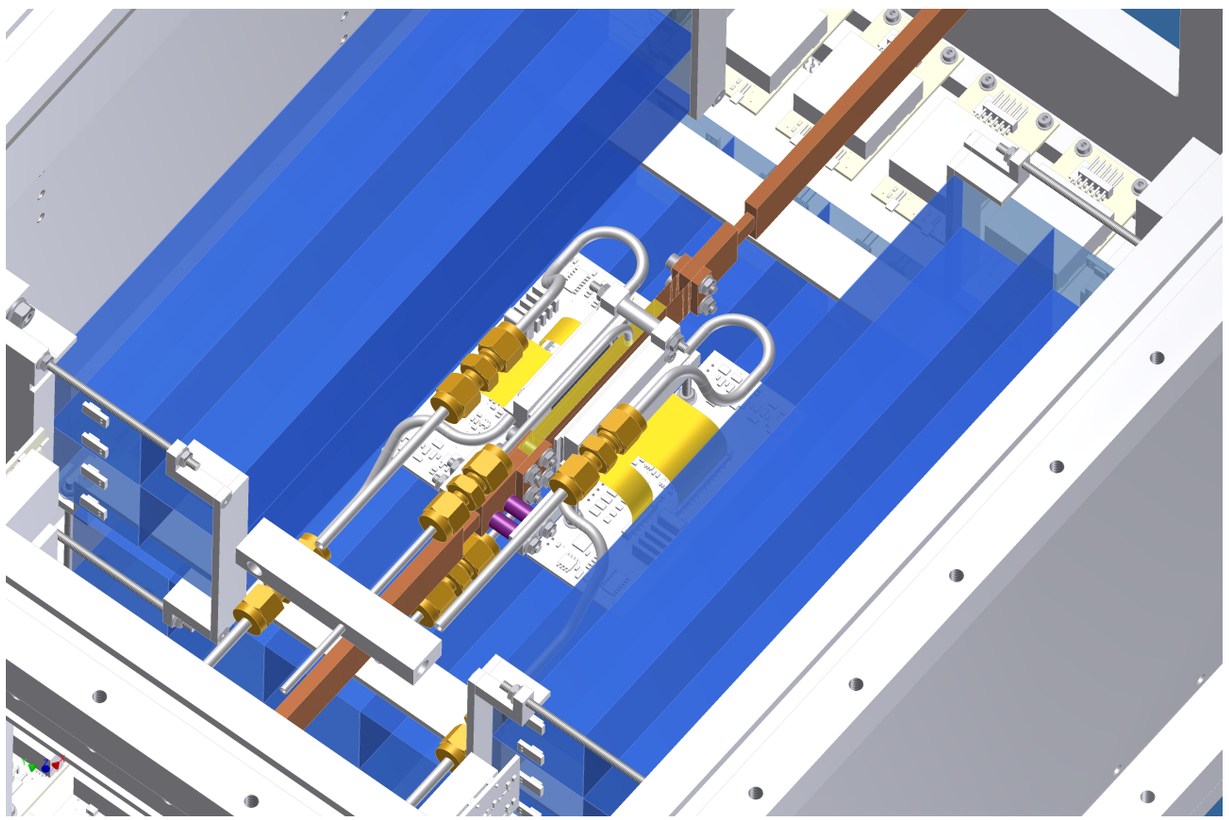
Excellence Cluster Universe, Technische Universität München,
- Garching, Germany

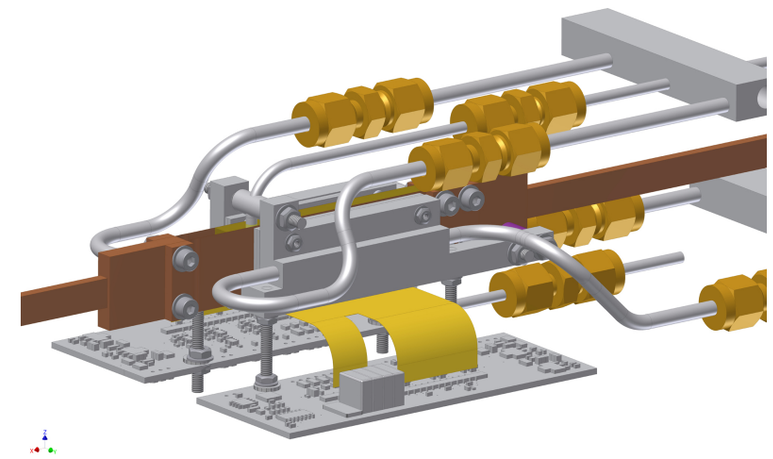
Compact target with active shielding

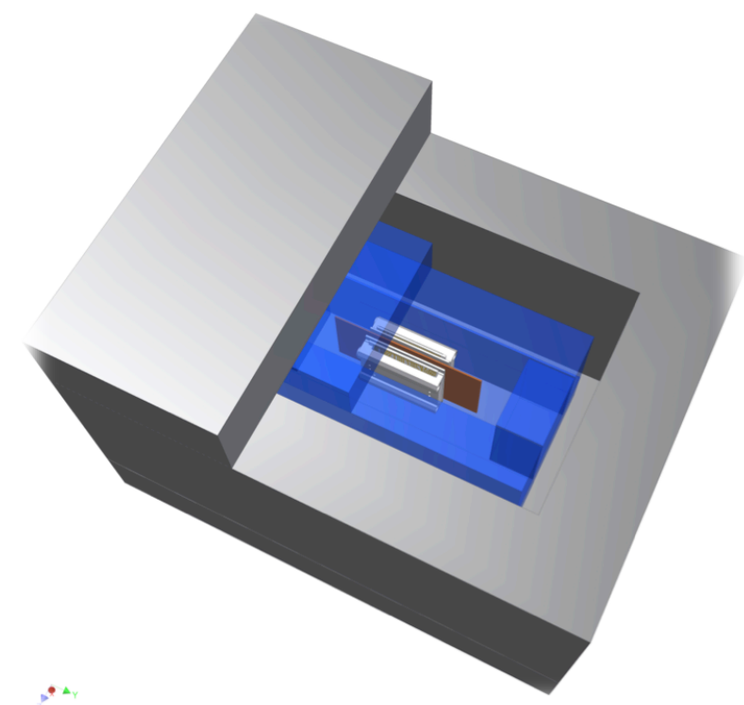
Stefan Meyer Institute

ÖAW Austrian Academy of Sciences

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



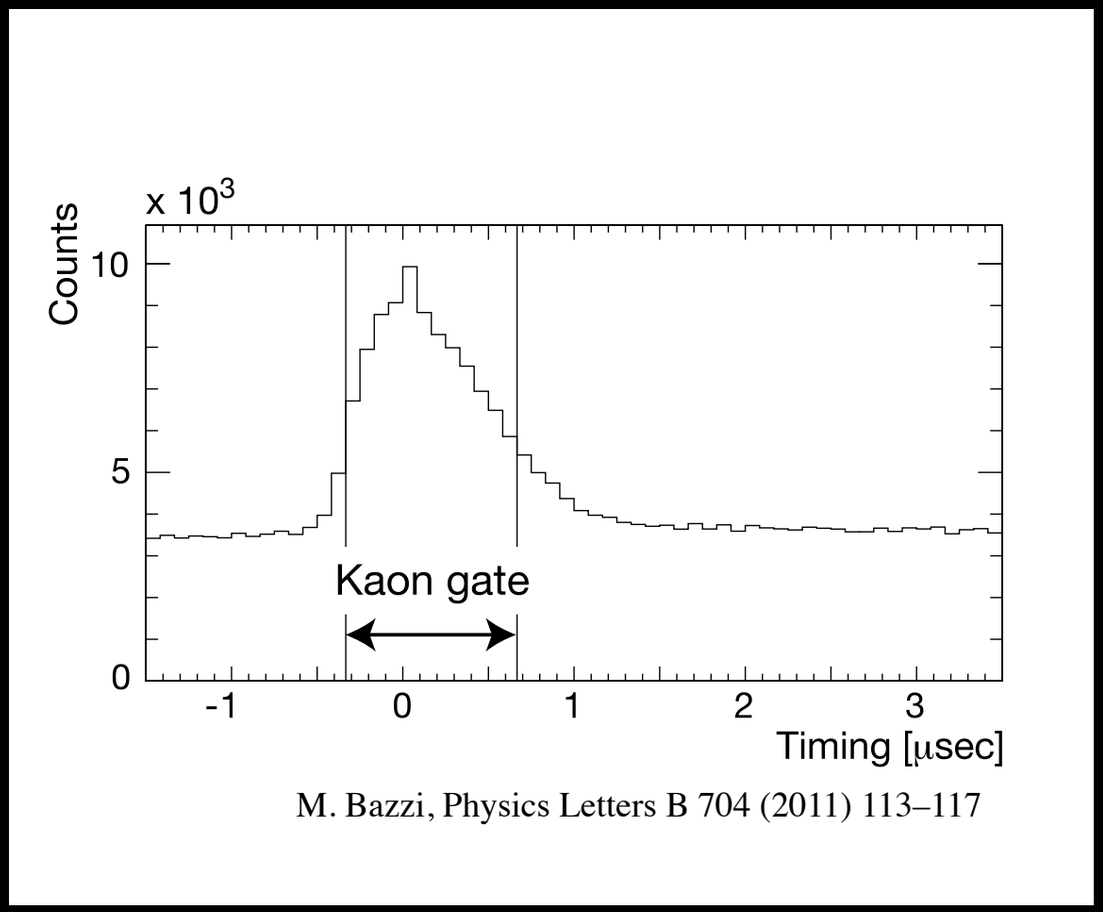


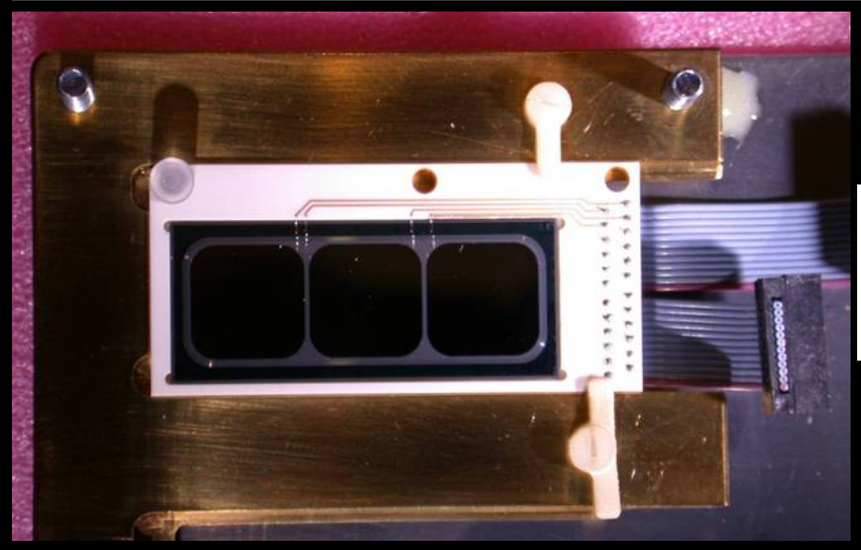


J. Marton, TAUP 2013

Silicon Drift Detectors with timing capability

SDD timing spectrum: SIDDHARTA experiment

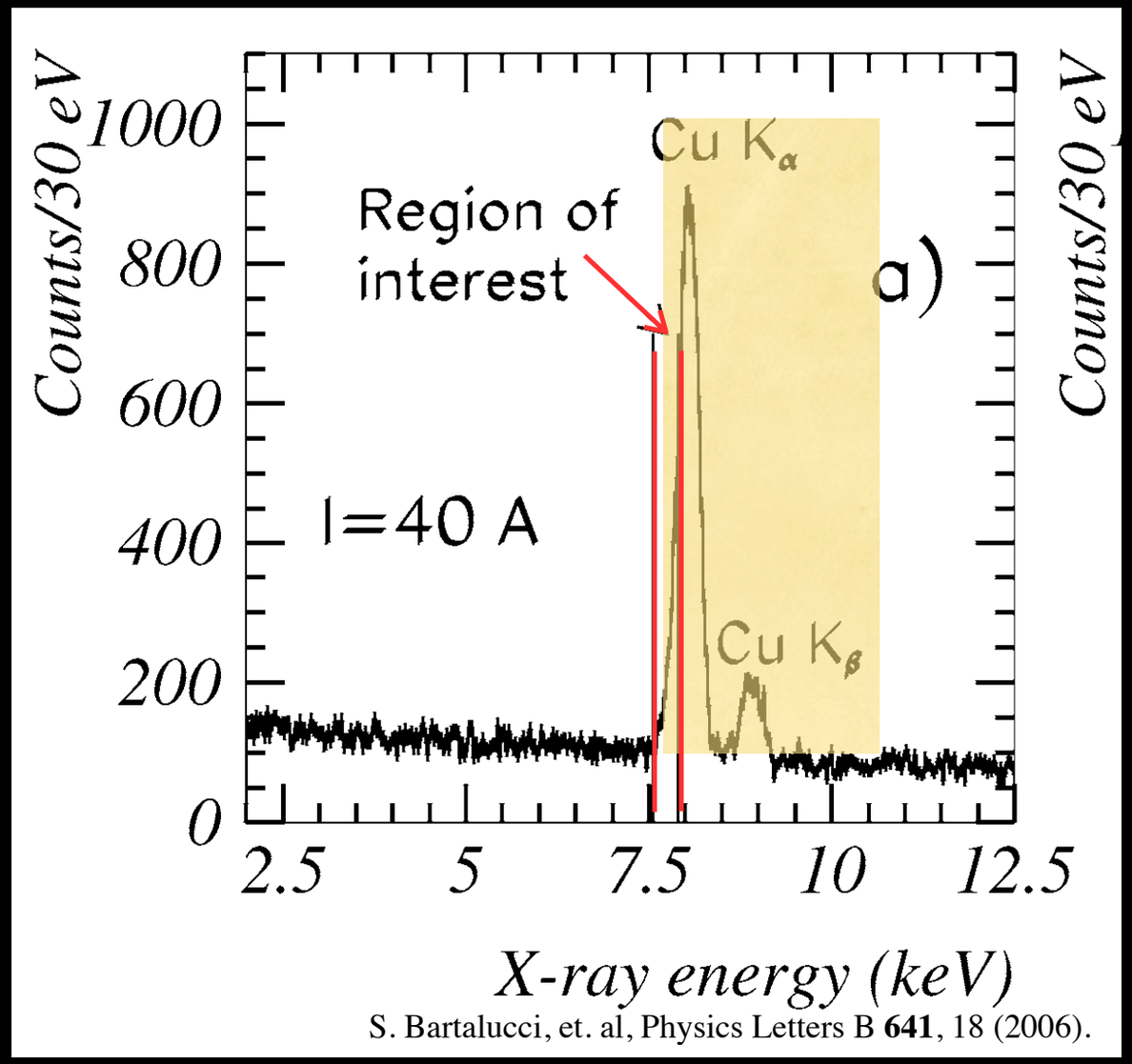




single array:
1 cm² x 3

SDD used in SIDDHARTA
for kaonic atom X-rays

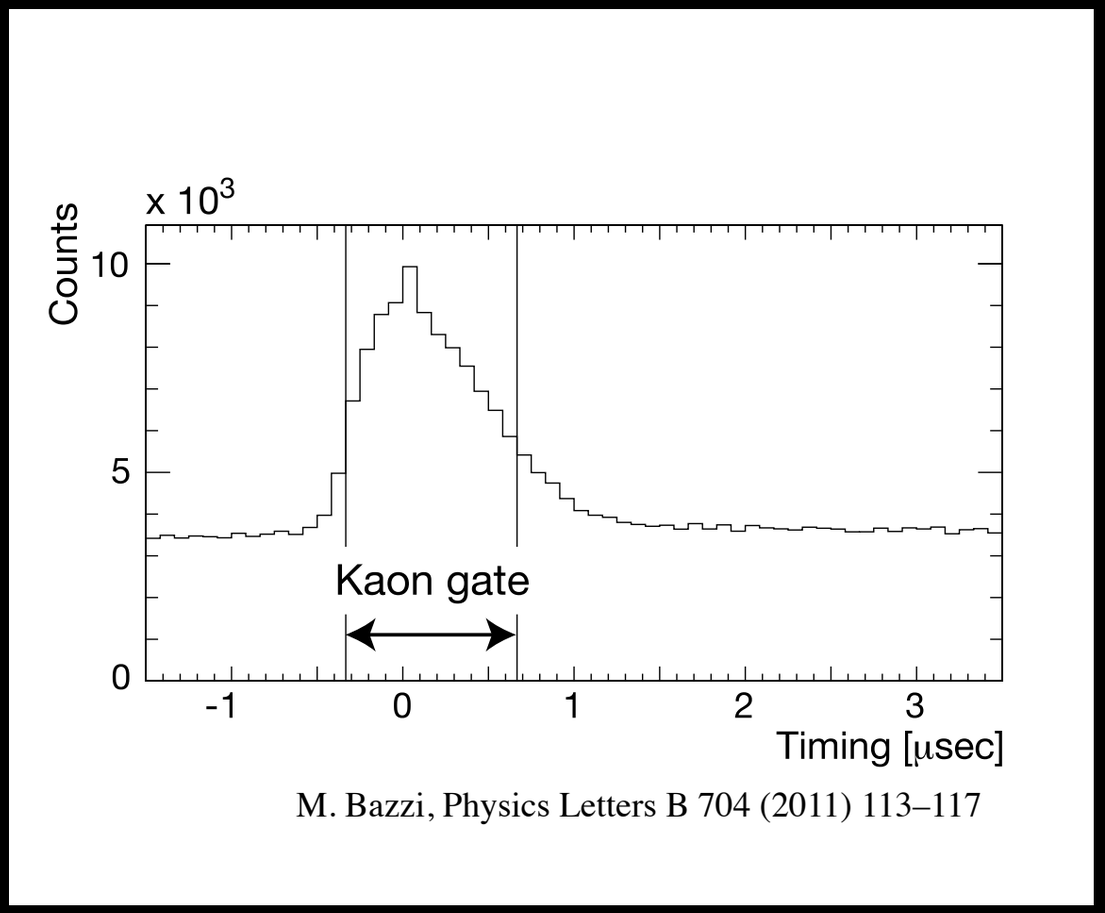
VIP CCD energy spectrum

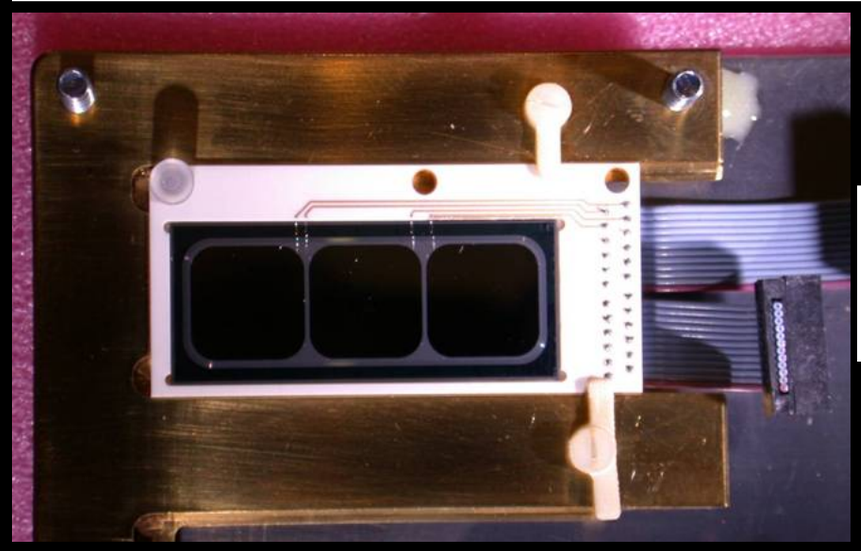


normal fluorescence X-rays from copper
are background
from cosimic-ray excited copper atoms

Silicon Drift Detectors with timing capability

SDD timing spectrum: SIDDHARTA experiment





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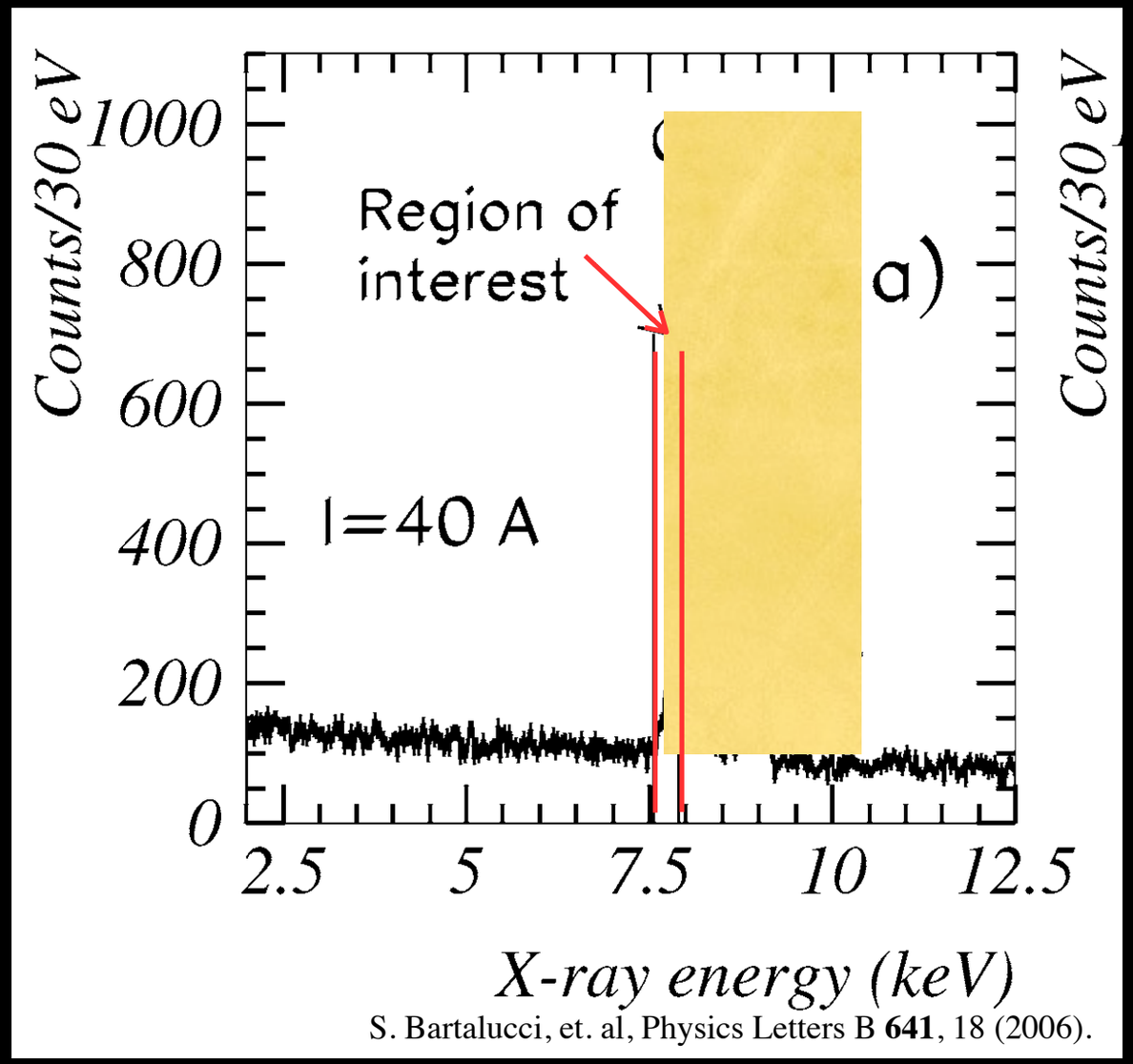
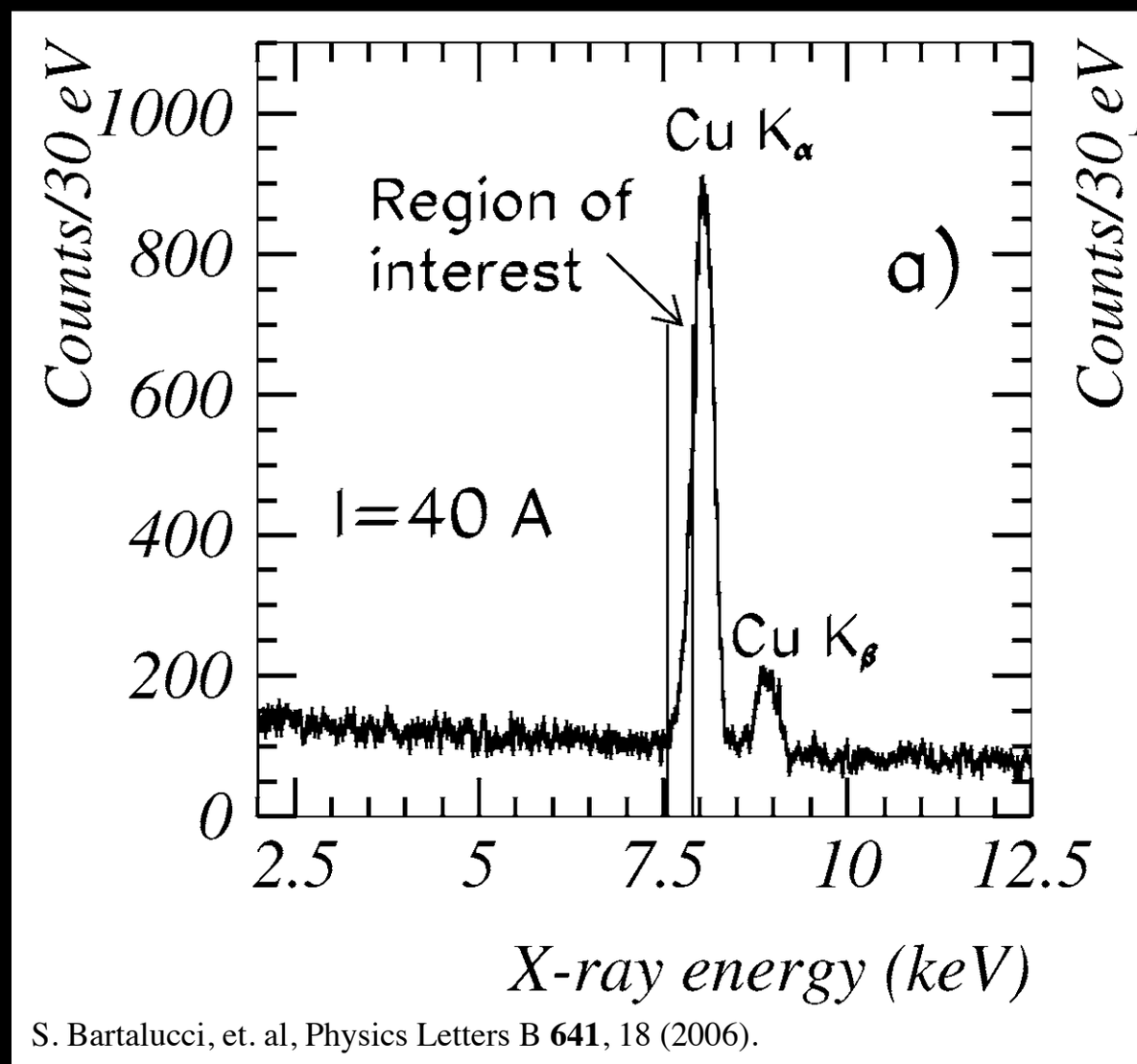


normal fluorescence X-rays from copper are background,
from cosmic-ray excited copper atoms
→ can be excluded using time information

CCD to SDD - Energy Resolution

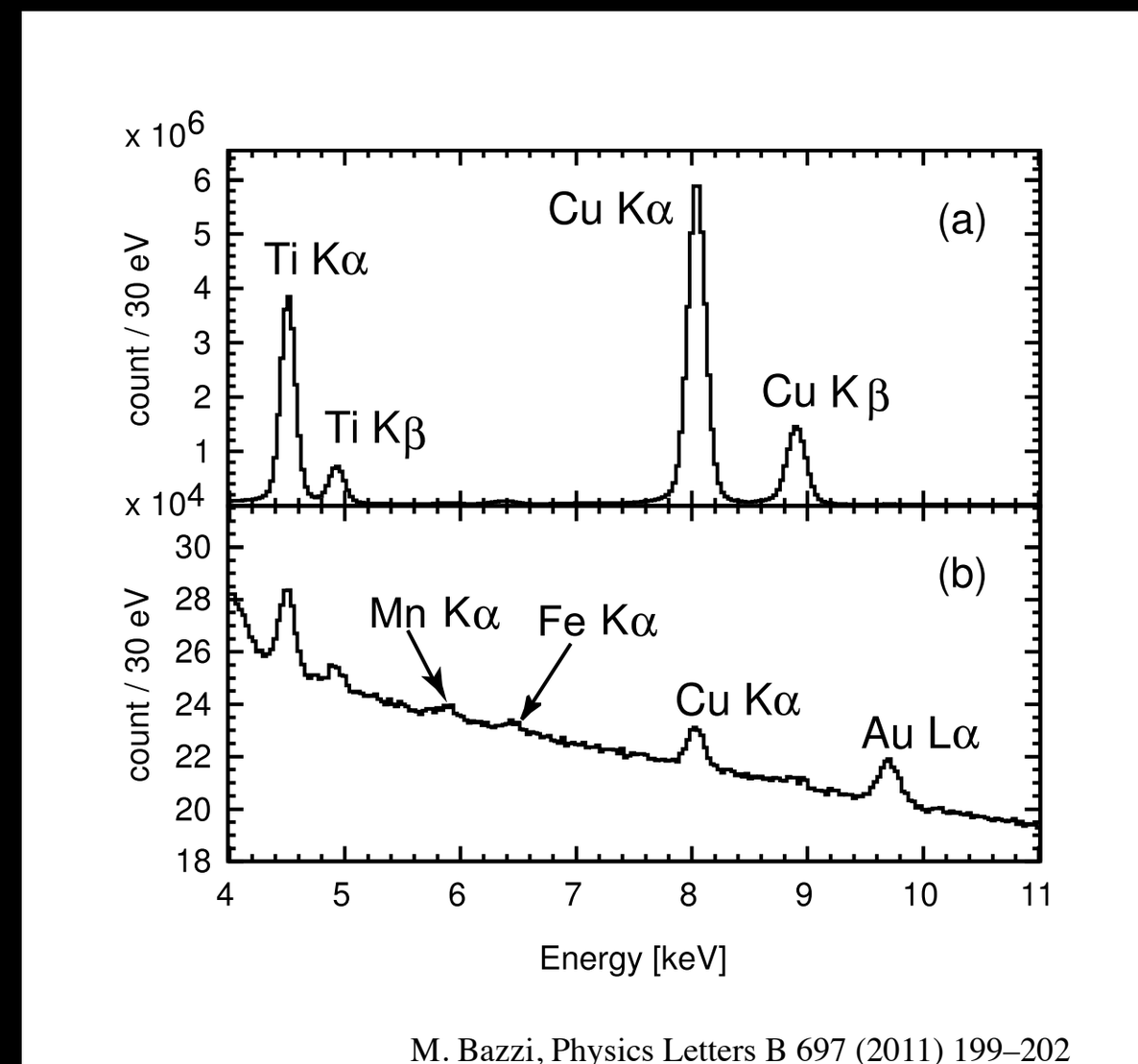
VIP



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

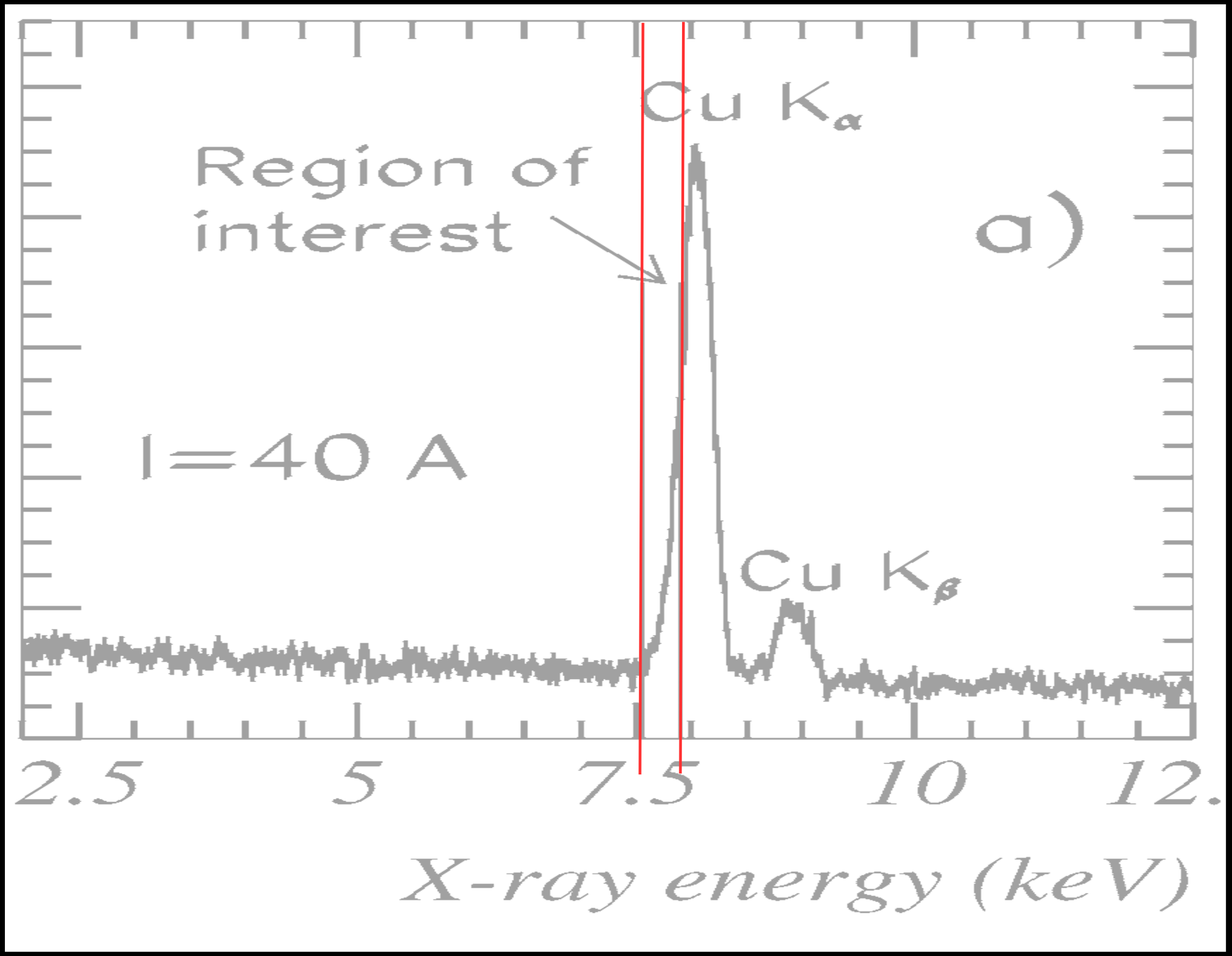
FWHM 340 eV
@ 8 keV

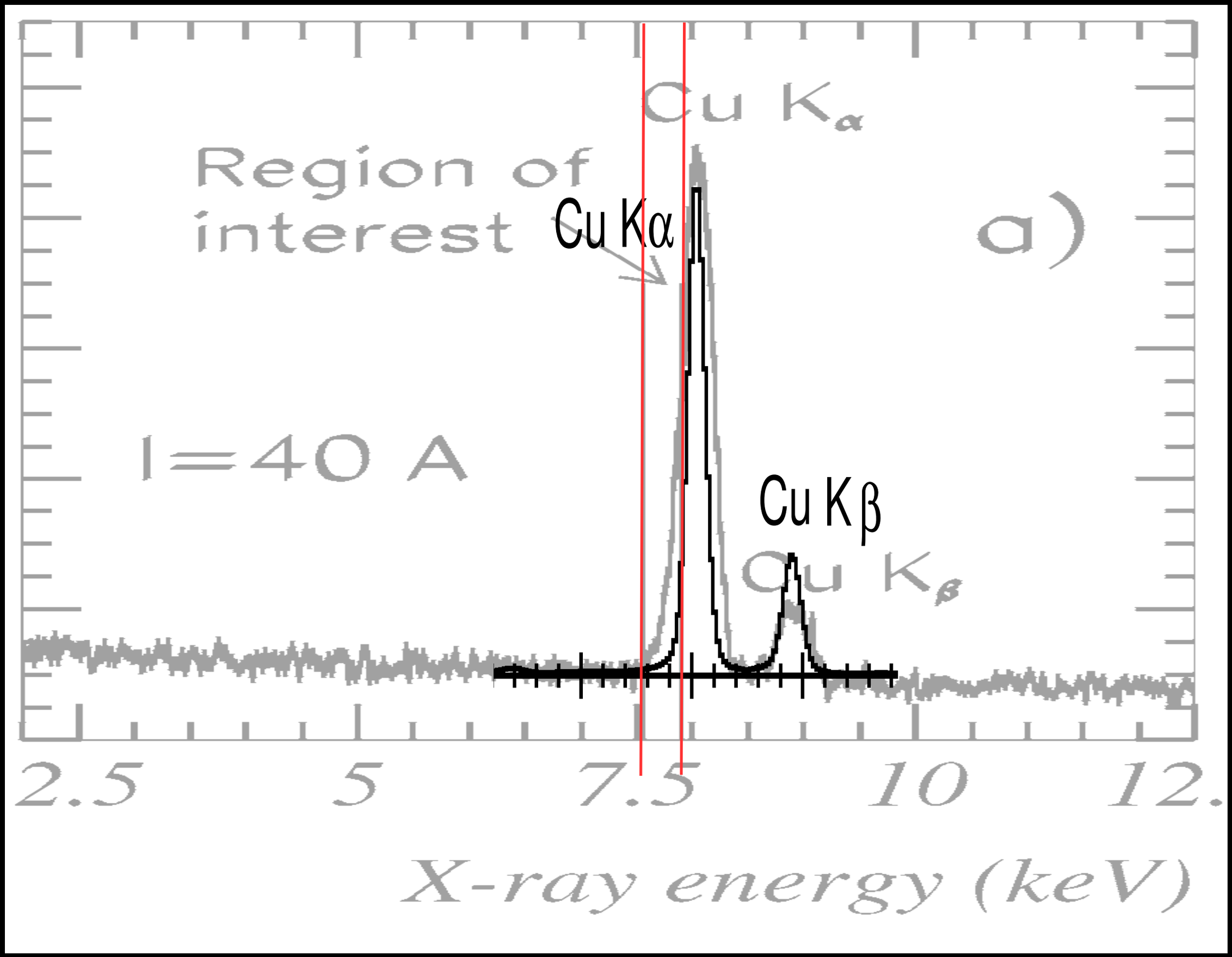
SIDDHARTA



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

FWHM 170 eV
@ 8 keV


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


Cu Kα
Region of interest
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a)
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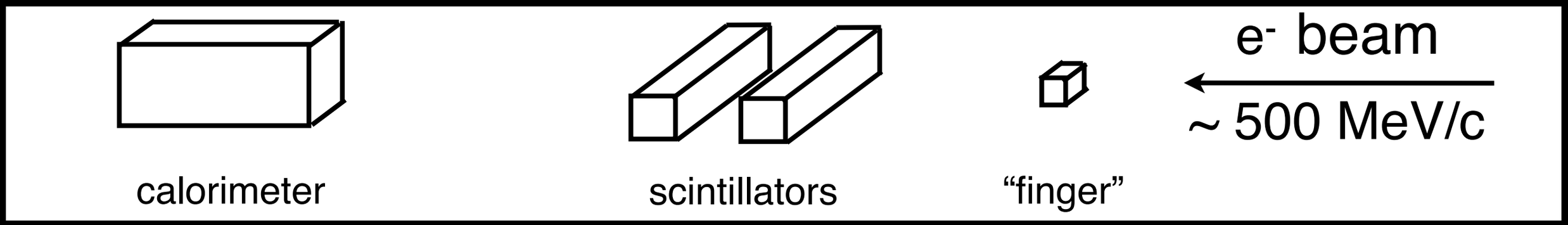
X-ray energy (keV)

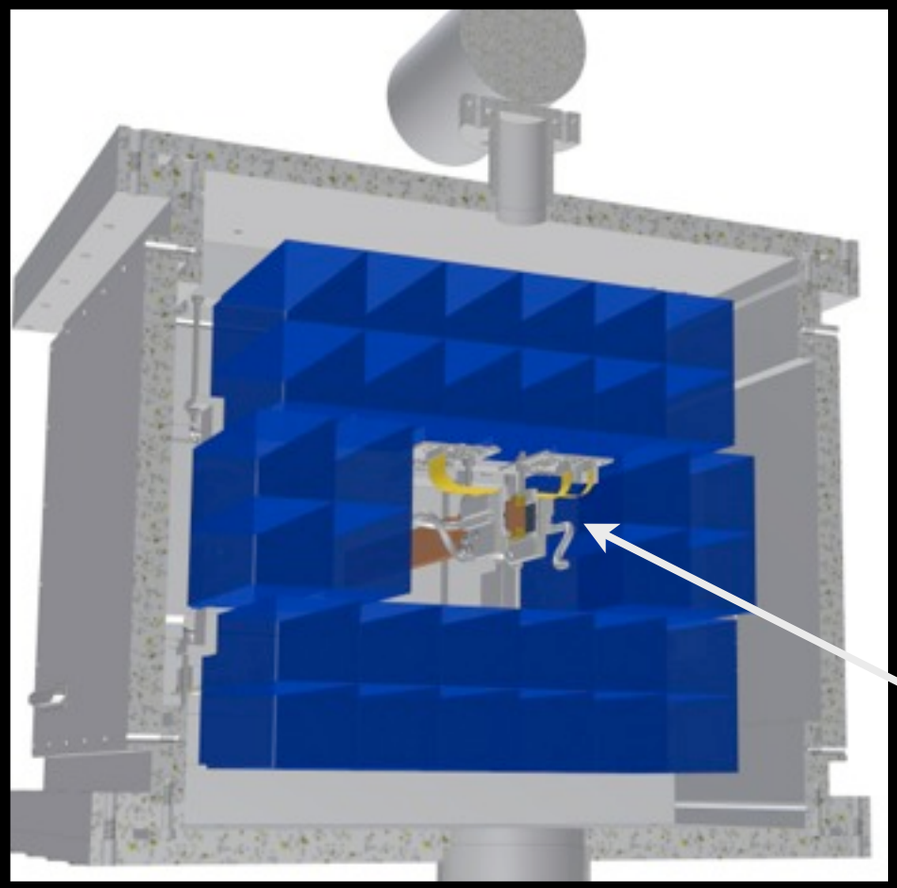
Preparation of VIP-2

Beam Test Facility test for scintillators

Dec. 2013, LNF



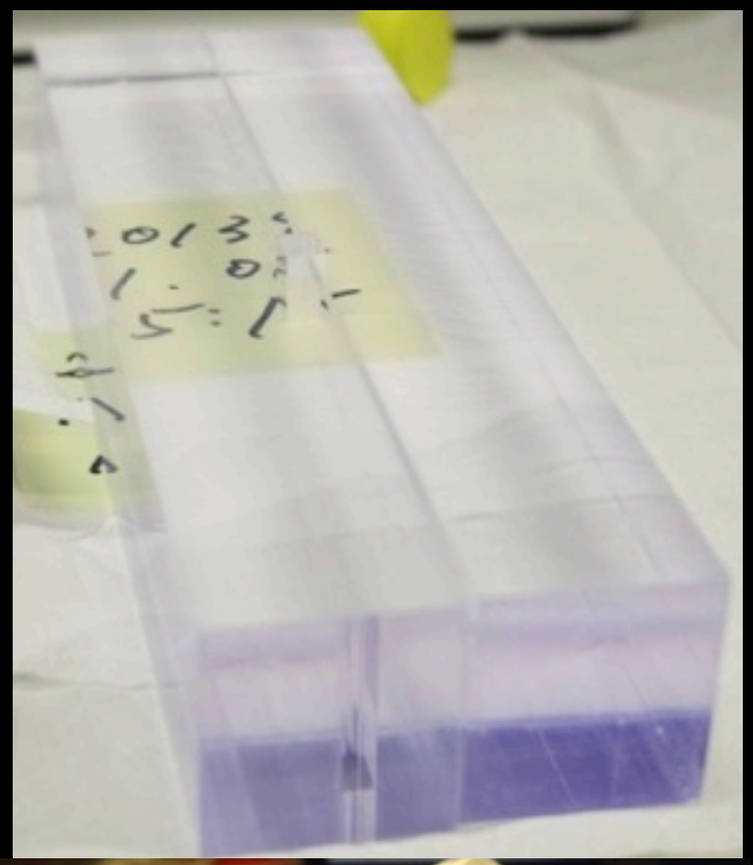
timing performance, efficiency test



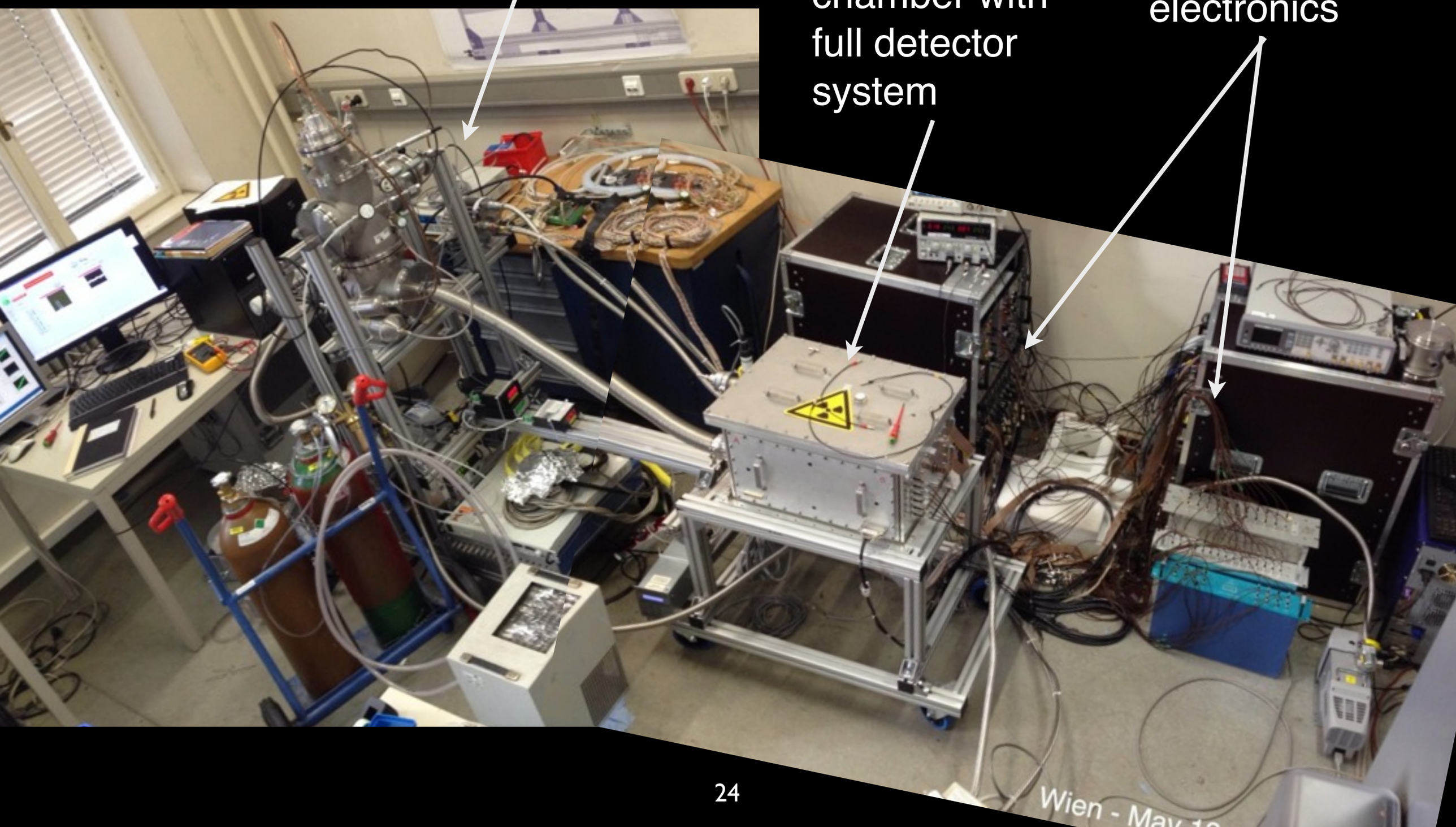
artist cut-away view of VIP-2 setup

3 x 2 SDDs

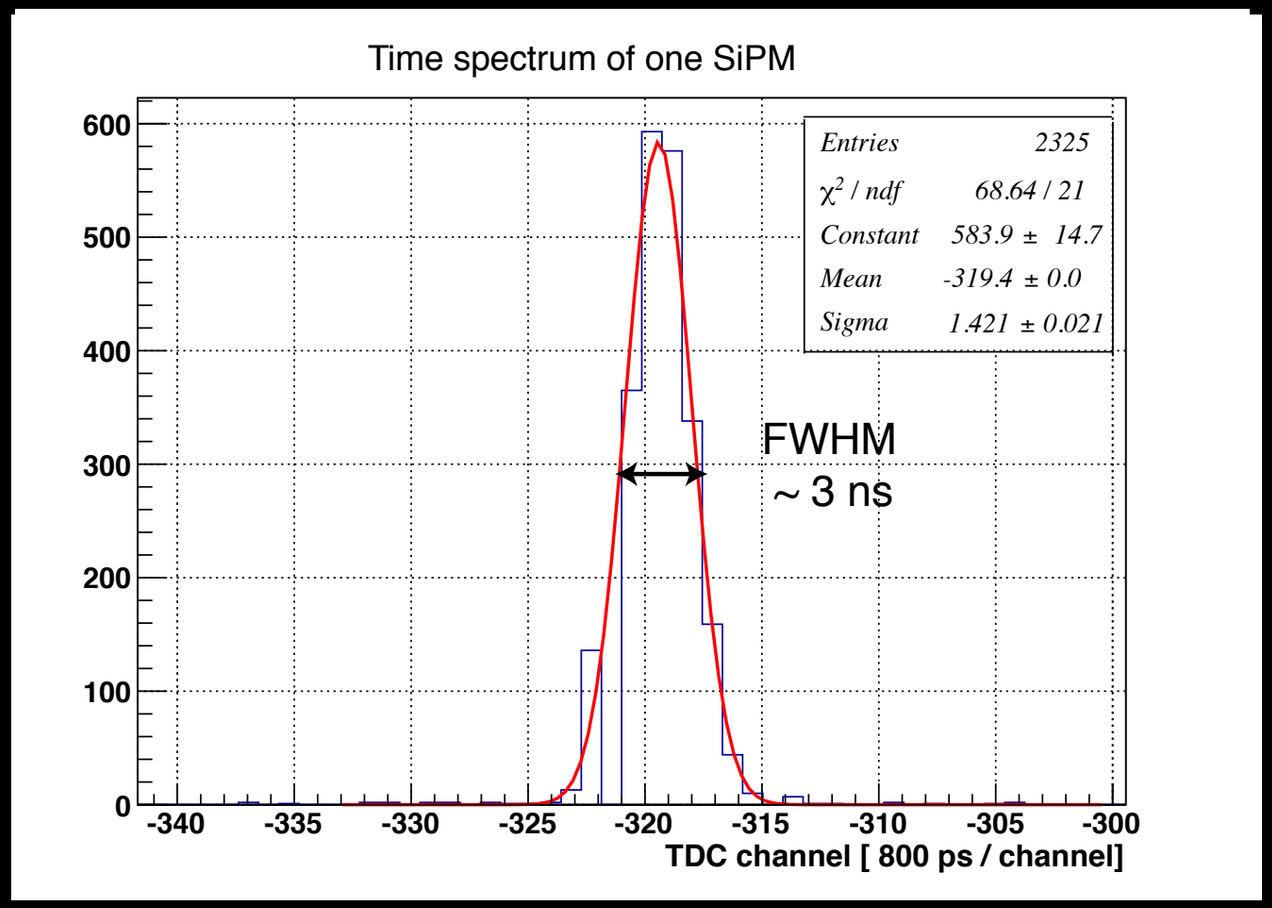
scintillator detectors as active shielding, with readout by SiPMs



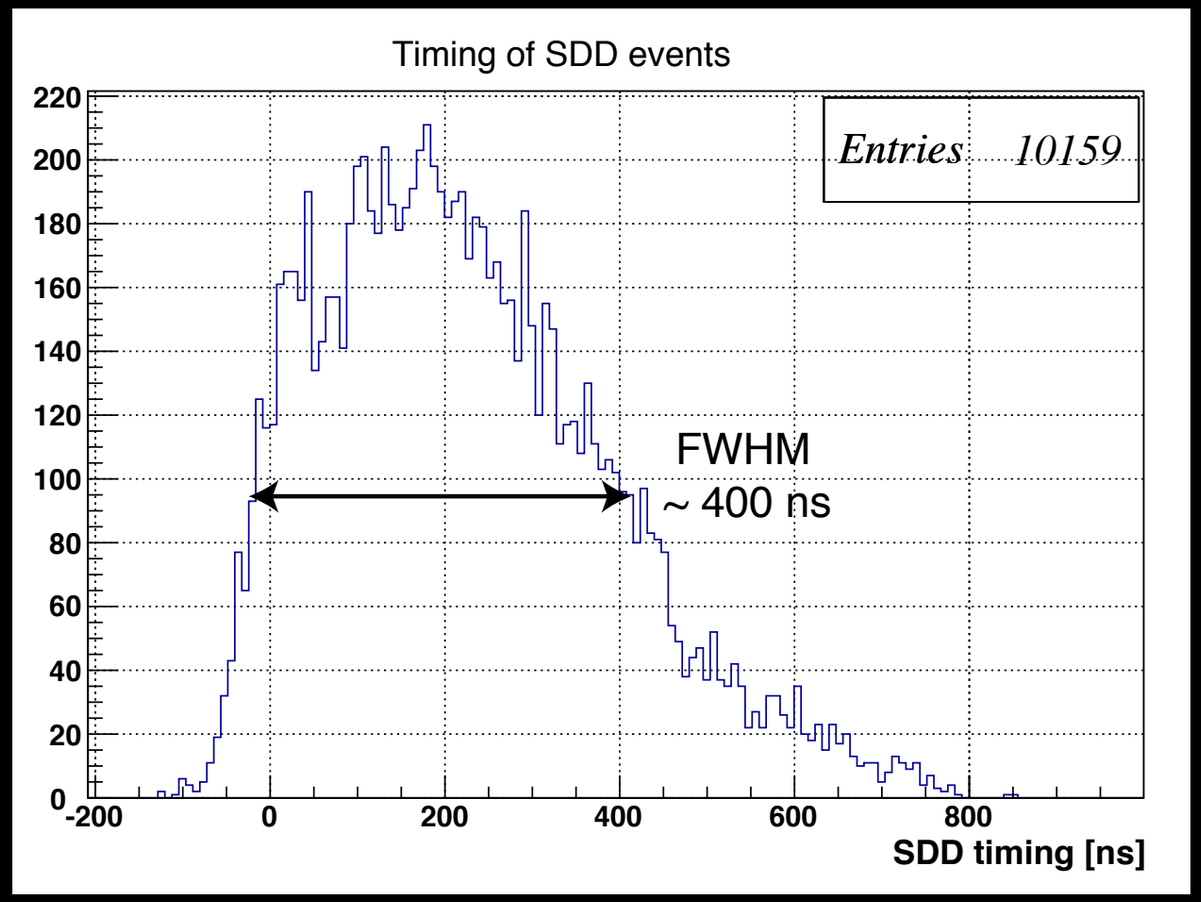
Final setup at SMI under test



Detector performances



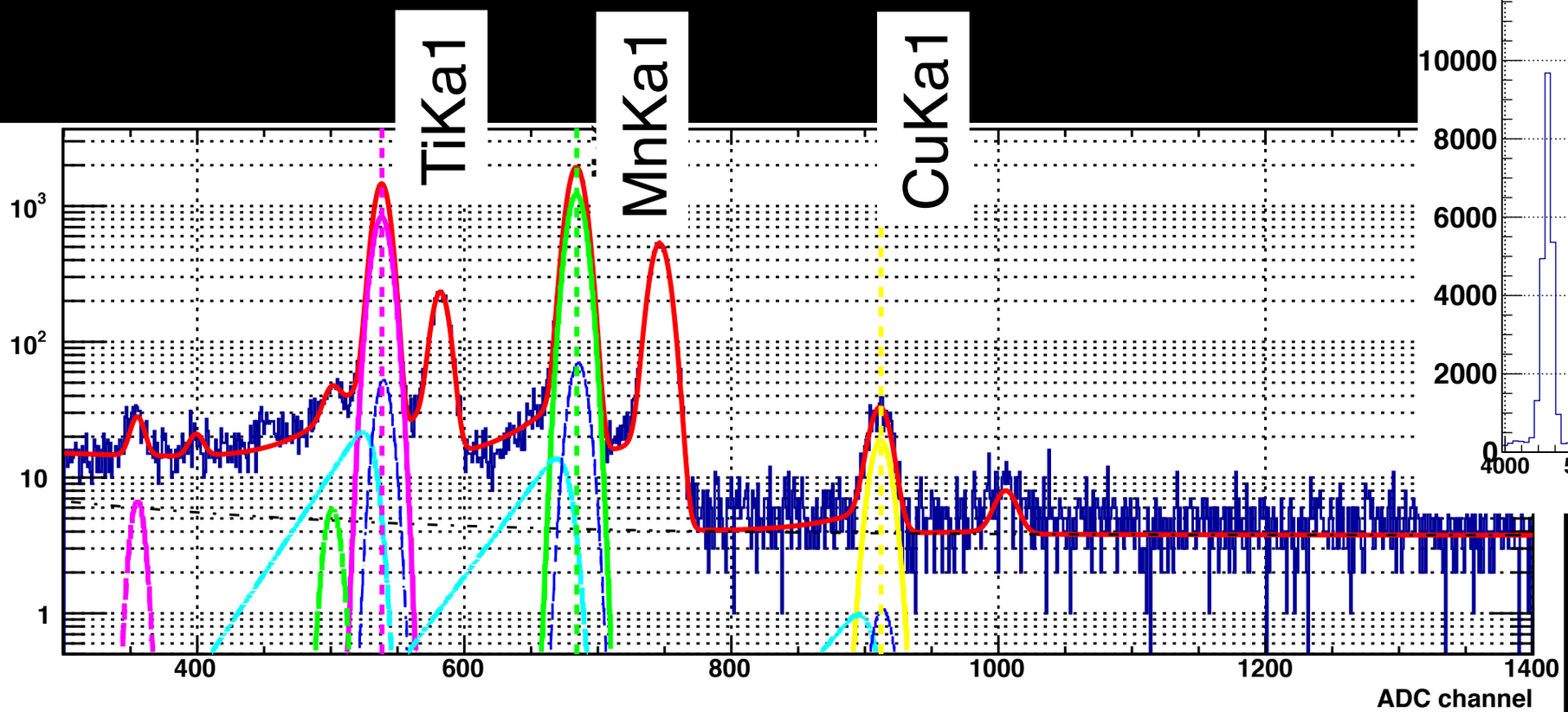
time resolution of scintillator from BTF measurement

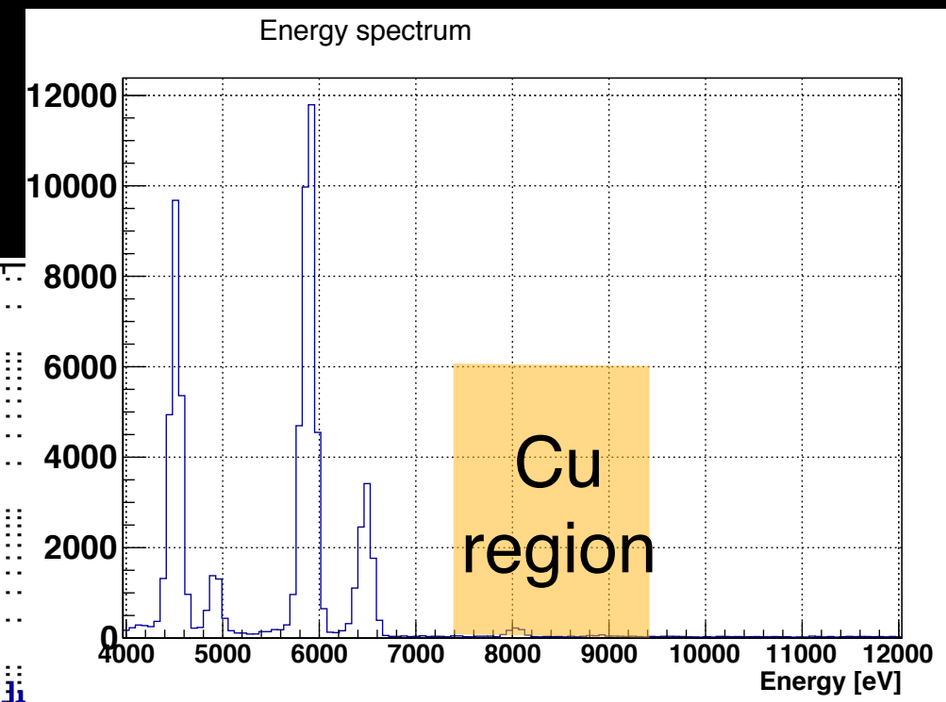


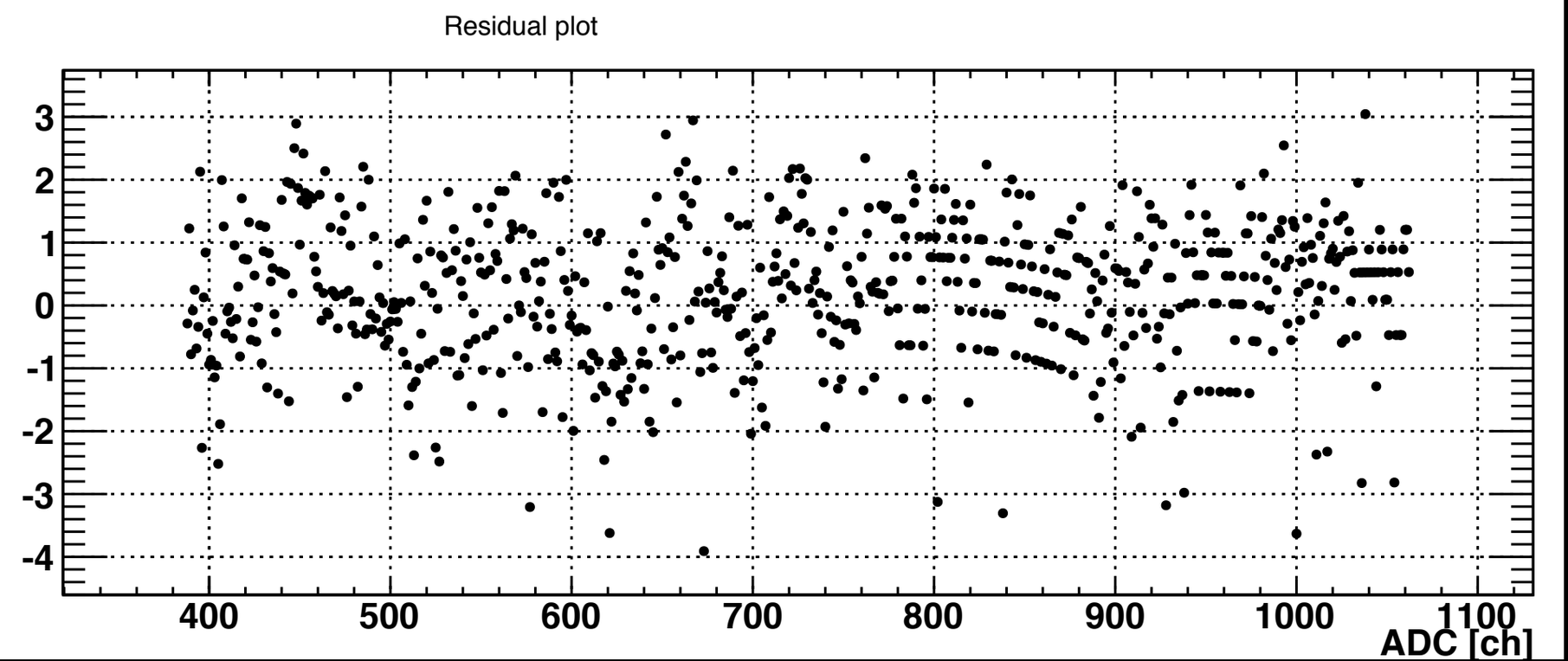
time resolution of SDDs from test setup measurement of cosmic rays

Detector performances

Energy calibration of the SDDs







FWHM @ 6 keV
147 eV

Andreas Pichler:
Application of photon detectors in the experiment to test Pauli Exclusion Principle

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

- background and stability measurement at SMI, Vienna;

- transportation of the final setup to LNGS within 2015, for long term data taking.

Summary

- Pauli Exclusion Principle, fundamental yet a postulate, open to experimental test, no quantitative presentation for small amount of violation yet;

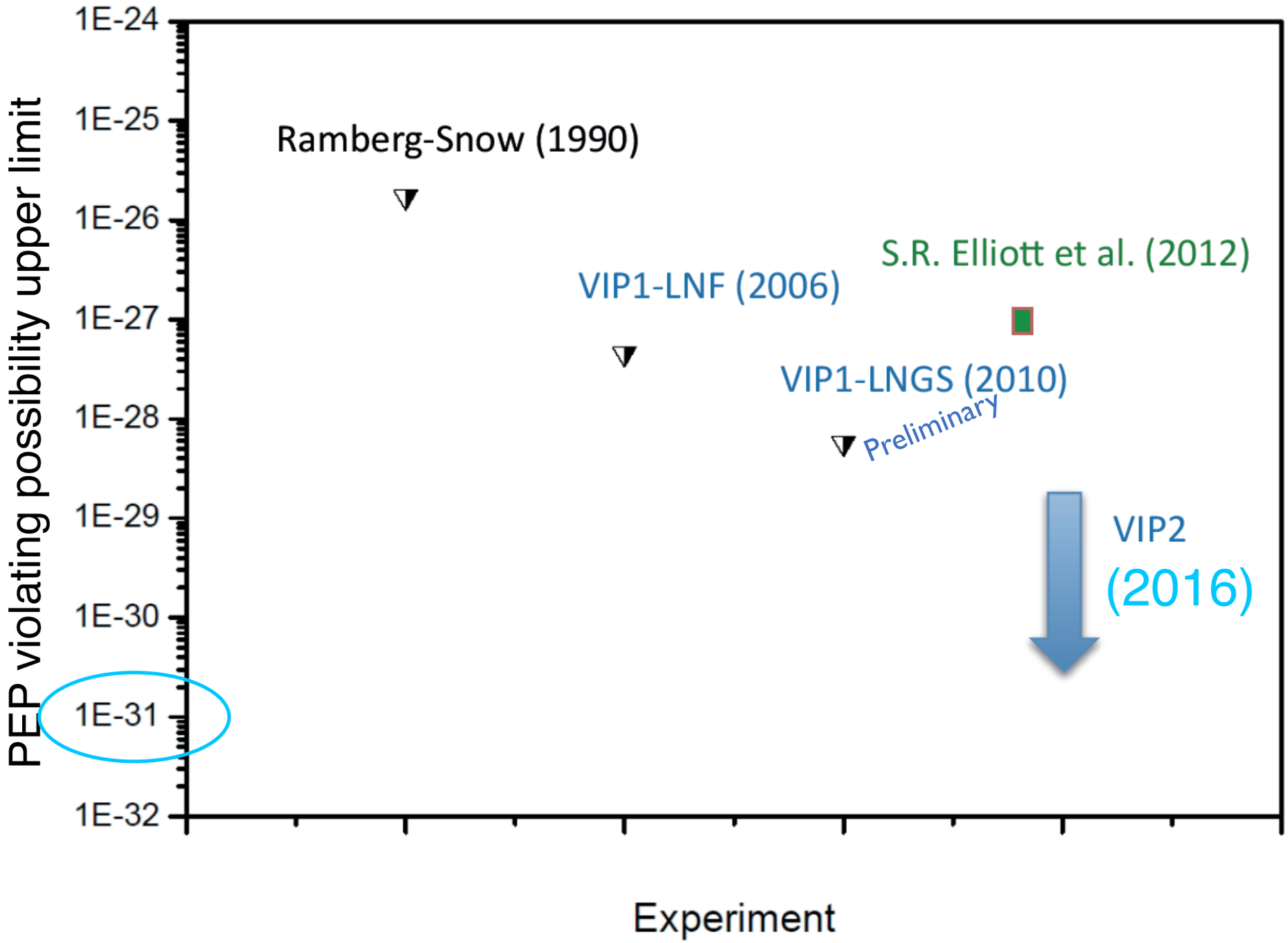
- the method of Ramberg & Snow (RS) searches for PEP-forbidden transition of electron;

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

- VIP-2 will improve sensitivity by two orders of magnitude.

- Possibilities of violation? Serendipity?

Towards VIP-2



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

Spare

Motivation
- in the words of W. Pauli

PEP lacks a clear, intuitive explanation

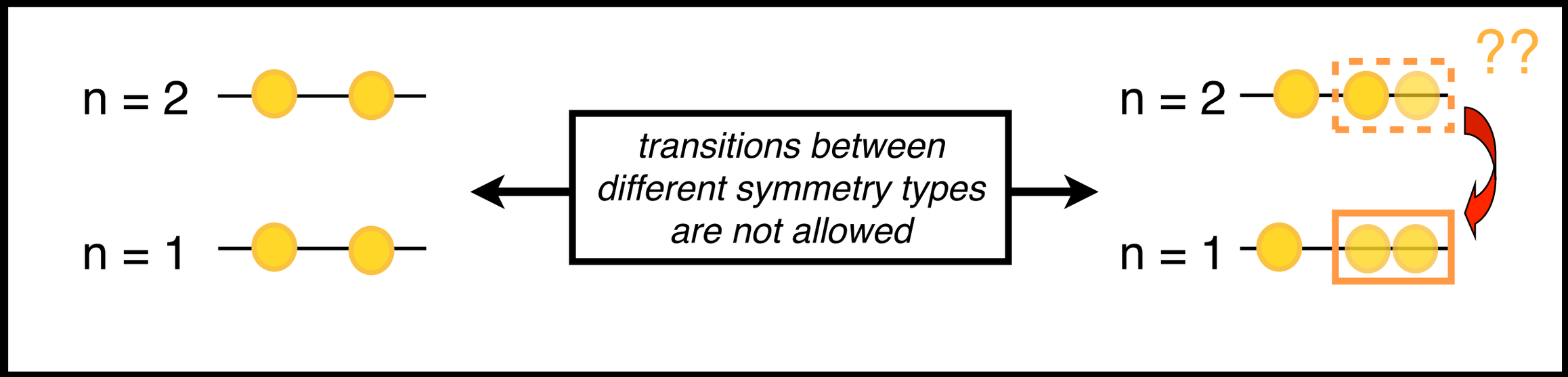
... Already in my original paper I stressed the circumstance that I was unable to give a logical reason for the exclusion principle or to deduce it from more general assumptions.

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

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?

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

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 mean absorption length 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:

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

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

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

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

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

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

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

L. Sperandio 2007

Analysis of VIP with RS method:

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

$$D = 0.088m$$

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

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

$$f_g \approx 0.01$$

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

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

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

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

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

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}	
$e^-_I + \mathrm{Pb} \rightarrow \check{\mathrm{Pb}}$	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