Testing the Pauli Exclusion Principle for electrons

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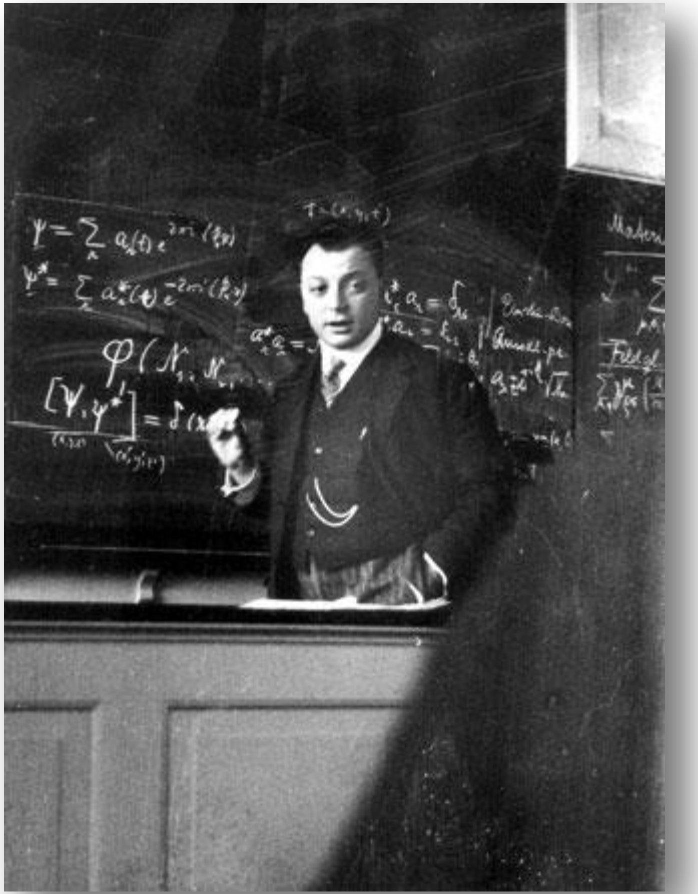
Pauli 75 years ago

"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, Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren, Zeitschrift für Physik 31 (1925) 765.



Identical particles – spin connection

> *"Roughly speaking, to say of two things that they are identical is nonsense, and to say of one thing that it is identical with itself is to say nothing at all"*
>
> Wittgenstein, Tractatus 5.5303

Symmetric states → bosons (integral spin)

Anti-symmetric states → fermions (half-integral spin)
at most 1 particle per state

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

The start of speculations on PEP violation

February 1964: The Ω^- was experimentally discovered at Brookhaven National Lab.

If Ω^- is a 3-quark state consisting of 3 s quarks then one faced a **problem with the Pauli exclusion principle** (quarks are spin ½, fermions) and the spin is parallel.

Theoretical models with parafermions instead strict fermions emerged and with precision experiments PEP violation was searched.

The PEP was finally reconciled by introducing a further degree of freedom of quarks – **the color**.

PEP Tests

In principle four methods:

- Search for non-Paulian nuclei

  E. Nolte *et al., Nucl. Instrum. Methods Phys. Res. B* ***52, 563*** (1990).

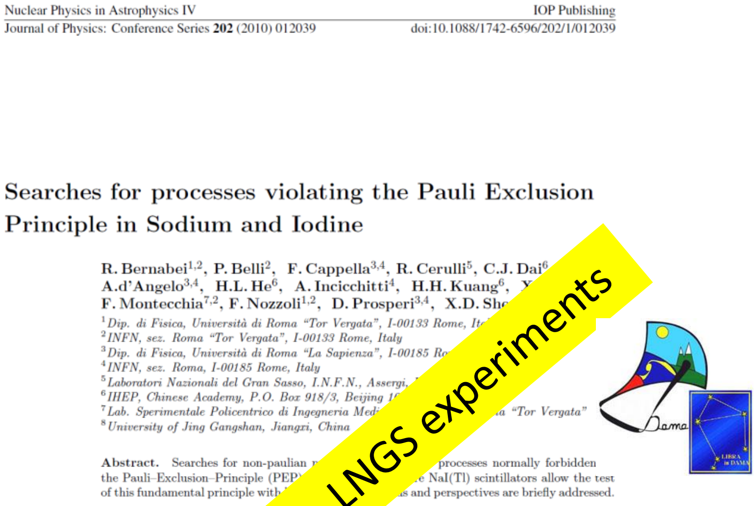
- Search for Pauli-forbidden nuclear transitions (e.g. Borexino@LNGS, 278t scint.)

- Search for non-Paulian atoms

  E. Nolte *et al., Z. Phys. A* ***340, 411 (1991).***

- Search for Pauli-forbidden atomic transitions → VIP

Recent papers from LNGS experiments



Nuclear Physics in Astrophysics IV — IOP Publishing

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Searches for processes violating the Pauli Exclusion Principle in Sodium and Iodine

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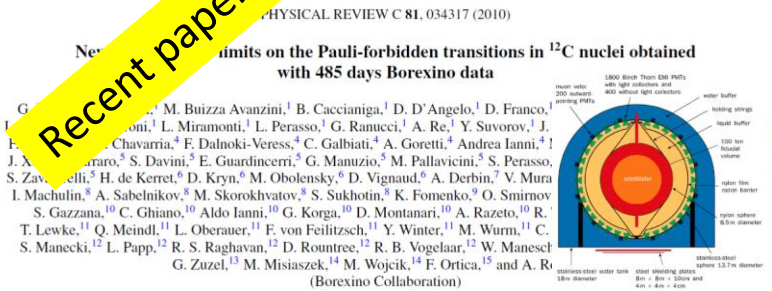
Abstract. Searches for non-paulian processes normally forbidden the Pauli–Exclusion–Principle (PEP) e NaI(Tl) scintillators allow the test of this fundamental principle with s and perspectives are briefly addressed.



PHYSICAL REVIEW C **81**, 034317 (2010)

Ne limits on the Pauli-forbidden transitions in ^{12}C nuclei obtained with 485 days Borexino data

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S. Manecki,[12] L. Papp,[12] R. S. Raghavan,[12] D. Rountree,[12] R. B. Vogelaar,[12] W. Manesch
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(Borexino Collaboration)

e.g. γ-decay ^{12}C to Pauli-forbidden nucleus
$\tau \geq 5 \times 10^{31}$ y → PEPV(rel. strength)$\leq 2.2 \times 10^{-57}$

Roll Over, Wolfgang?

New experiments seek violations of the Pauli exclusion principle

The Pauli exclusion principle, named for its author, the cantankerous Austrian physicist Wolfgang Pauli, is a keystone of modern physics. Indeed, without it physics, if not matter, would collapse. Physicists consider the principle to be airtight. But now two theorists at the University of Maryland at College Park have formulated a relativistic quantum field theory that could poke a small but detectable hole in Pauli's principle.

The exclusion principle is invoked to explain why electrons in an atom occupy a succession of "orbits" at progressively higher energy levels instead of tumbling en masse to the ground state. Pauli proved that two particles of a class called fermions (such as electrons, protons and neutrons) cannot occupy the same orbit if they have identical quantum numbers. Electrons have a quantum number called spin, which can be either up or down. Thus each orbit can accommodate up to two electrons as long as their spins point in opposite directions.

Last year two Russian physicists, A. Yu. Ignatiev and V. A. Kuzmin, published a simple model that allows two identical fermions to fill one state. Intrigued, Maryland's Oscar W. Greenberg and Rabindra N. Mohapatra decided to attempt a more complete theory based on that model. They published their results last year in *Physical Review Letters*. The new theory allows rare "paronic" states to exist, in which two identical fermions can occupy a state simultaneously, violating the exclusion principle.

If paronic states exist, it may be possible to observe them. In a paronic atom, for example, one of the orbits would be filled by two electrons whose spins are parallel. The parallel-spin electrons would interact differently from antiparallel-spin electrons, and so the energy level of a paronic orbit would not be the same as that of a normal orbit. This difference should show up as tiny aberrations in the radiation that is emitted when electrons jump between atomic orbits.

Daniel E. Kelleher of the National Bureau of Standards will be searching for the simplest of such atoms, paron-

cancel. In paronic helium, however, the spins are parallel and the magnetic moments add up. Kelleher will use a magnet to pull such atoms out of liquid helium. Laser spectroscopy would then reveal whether any of the selected atoms exhibit the ground-state energy of paronic helium, which differs by one part in 15,000 from that of ordinary helium. Robert L. Park, Erik J. Ramberg and Richard L. Talaga at Maryland propose two separate searches in other elements.

It will be some years before results are in. Meanwhile Greenberg and Mohapatra are examining the consequences of their theory. In addition to the exclusion principle, the new theory violates the CPT theorem, a pillar of quantum field theory. The situation might be salvaged, Greenberg says, by introducing the extra space dimensions that string theorists say curl around each particle. Greenberg speculates that CPT and the exclusion principle may be violated only in ordinary spacetime and may be conserved in the spacetime that includes these hidden dimensions. If the idea pans out, he says, the experiments could provide the long-awaited test of string theory.

—*June Kinoshita*

Quantum Holonomy

Phase shifts track a quantum system in "state space"

To understand the latest surprise served up by the quantum world take a pencil, lay it on th
pole of a globe and point it
direction of any line of longitu
radiates from the pole. Move t
cil down along the line to the
and, keeping it perpendicular
equator, move it along the equ
another longitude. Move the
back to the north pole along
longitude and you will find
though the pencil has returne
starting spot, it no longer point
the original line of longitude.

This is an example of a purely geometric effect, known as holonomy, resulting from the fact that the pencil was forced to trace out a circuit on the surface of a sphere while remaining parallel to the meridians. The holonomy caused by such "parallel transport" around a circuit on a curved surface is not limited to tangible ob-

abstract constructs in the microscopic realm of quantum physics.

In the quantum realm the state of a physical system is best regarded as a wave whose characteristics are determined by parameters, or physical quantities, that may affect the system. In the case of a photon such a parameter might be, say, its polarization (the direction of its associated electric field) or its intrinsic spin. Another important component of quantum waves is their phase: the positions of each wave's crests and troughs in relation to one another.

As was first pointed out in 1983 by Michael V. Berry of the University of Bristol, as a result of geometric holonomy a quantum system can exhibit different phases in its initial and final wave representations even though the system begins and ends with the same parameter values. The key to understanding how this can happen is to visualize all possible states of the system as points on the surface of a sphere in "state space." Because the initial and final states of the system are represented by the same point on the sphere, the intermediate states lie on a closed curve on the sphere.

The phase of the wave representing the system can then be envisioned as undergoing parallel transport (like the pencil on the globe) as the system goes from state to state around the curve, completing a circuit. As a consequence, when the system returns to its starting point it no longer has its original phase. In fact, the magnitude of the change in phase reveals the

photons began and ended in the same polarization state as those in the other split beam. A team headed by Raymond Y. Chiao of the University of California at Berkeley and Howard Nathel of the Lawrence Livermore National Laboratory tried altering the direction of the photons' momentum rather than their polarization. The team observed the predicted phase

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Growing interest since 1987

It is interesting to compare the number of papers published on the subject of small statistics violation before and after 1987. During 30 years prior to 1987 there were about a dozen of papers on the topic including pioneering works by Reines and Sobel (1974), Logan and Ljubicic (1979), Amado and Primakoff (1980) and Kuzmin (1984) while since 1987 the number of papers has grown to several hundreds.

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.”

Experiment of Goldhaber & Scharff-Goldhaber

(identification of beta-rays with atomic electrons; 1948)

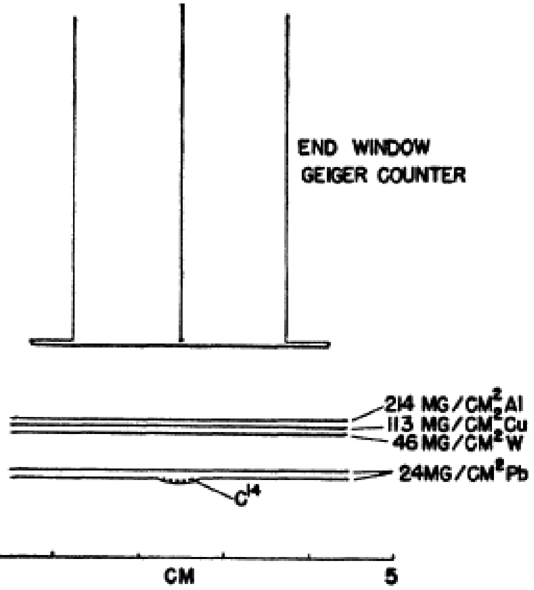
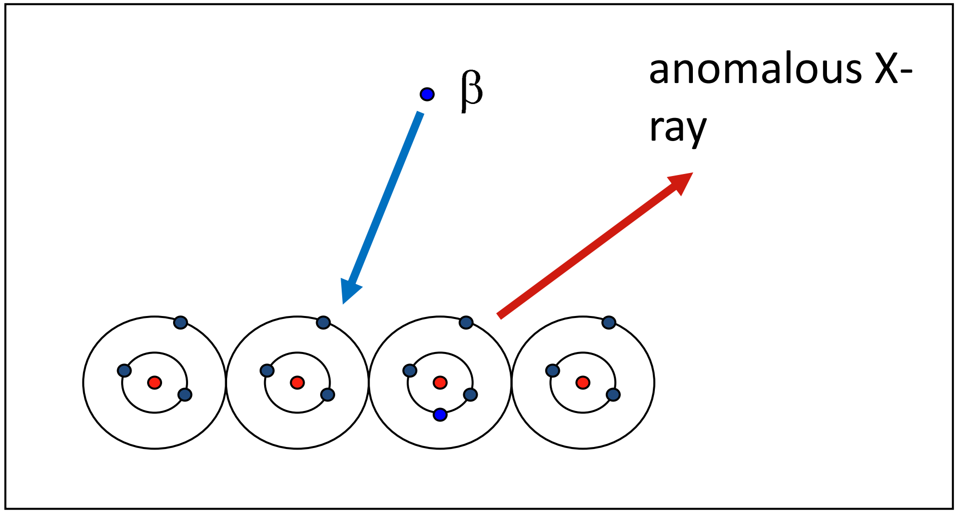
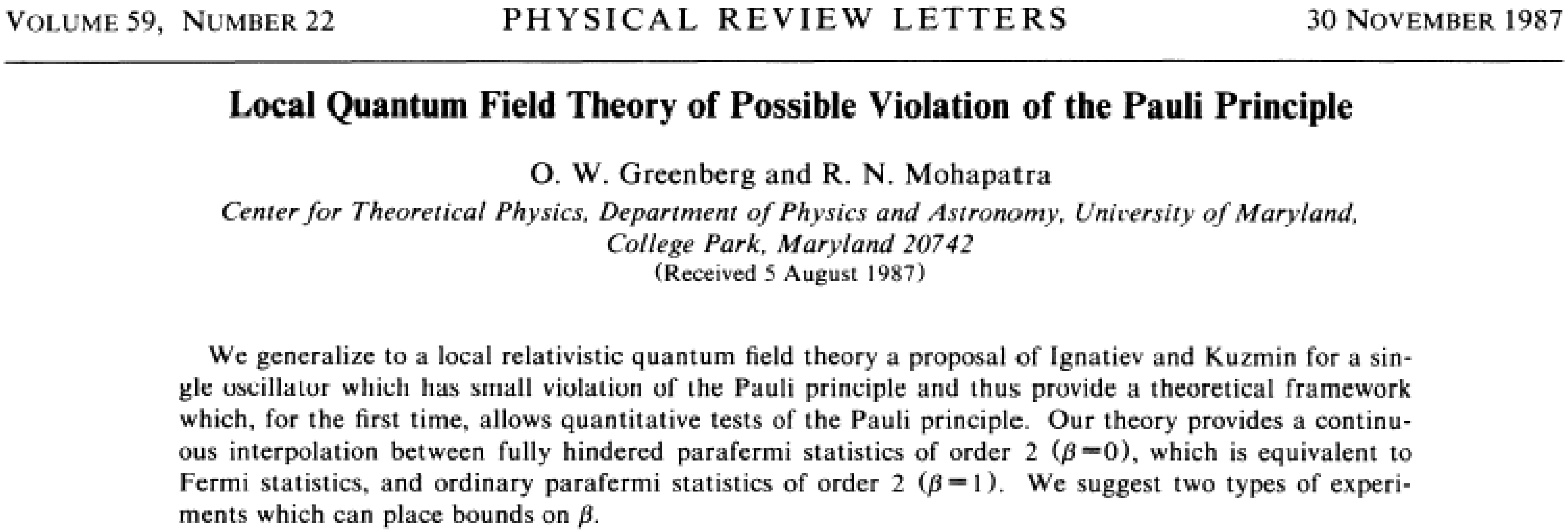


FIG. 1. Arrangement used in search for photons from beta-rays stopped in lead.

The data of Goldhaber and Scharff-Goldhaber were reinterpreted by Reines and Sobel to obtain a limit on the validity of Pauli Exclusion Principle in 1974



the origin of the first dedicated experiment (RS) can be traced back to George Snow, as quoted in a paper by Greenberg & Mohapatra (1987)



VOLUME 59, NUMBER 22 PHYSICAL REVIEW LETTERS 30 NOVEMBER 1987

Local Quantum Field Theory of Possible Violation of the Pauli Principle

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Center for Theoretical Physics, Department of Physics and Astronomy, University of Maryland,
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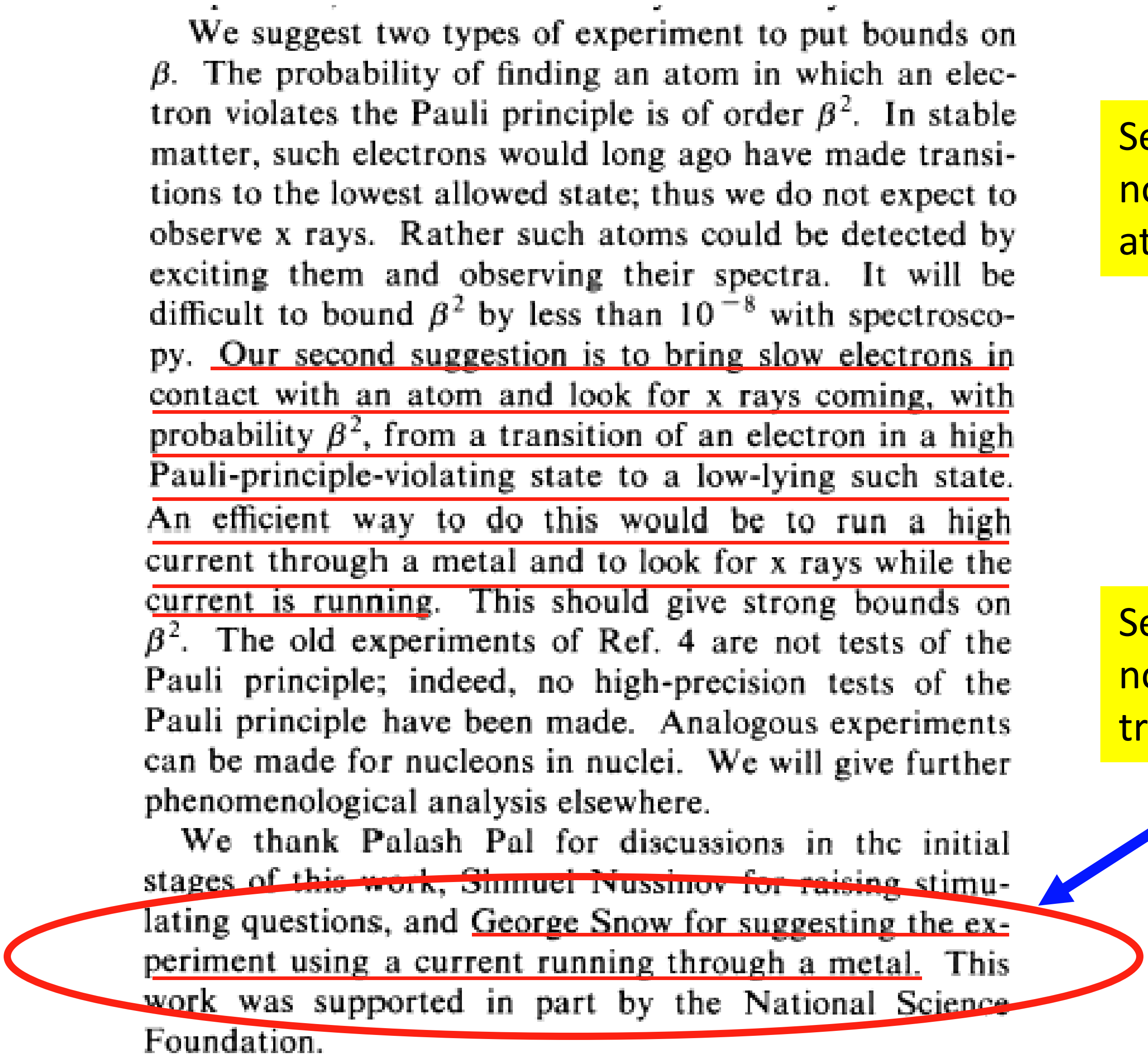
(Received 5 August 1987)

We generalize to a local relativistic quantum field theory a proposal of Ignatiev and Kuzmin for a single oscillator which has small violation of the Pauli principle and thus provide a theoretical framework which, for the first time, allows quantitative tests of the Pauli principle. Our theory provides a continuous interpolation between fully hindered parafermi statistics of order 2 ($\beta=0$), which is equivalent to Fermi statistics, and ordinary parafermi statistics of order 2 ($\beta=1$). We suggest two types of experiments which can place bounds on β.



We suggest two types of experiment to put bounds on β. The probability of finding an atom in which an electron violates the Pauli principle is of order β^2. In stable matter, such electrons would long ago have made transitions to the lowest allowed state; thus we do not expect to observe x rays. Rather such atoms could be detected by exciting them and observing their spectra. It will be difficult to bound β^2 by less than 10^{-8} with spectroscopy. Our second suggestion is to bring slow electrons in contact with an atom and look for x rays coming, with probability β^2, from a transition of an electron in a high Pauli-principle-violating state to a low-lying such state. An efficient way to do this would be to run a high current through a metal and to look for x rays while the current is running. This should give strong bounds on β^2. The old experiments of Ref. 4 are not tests of the Pauli principle; indeed, no high-precision tests of the Pauli principle have been made. Analogous experiments can be made for nucleons in nuclei. We will give further phenomenological analysis elsewhere.

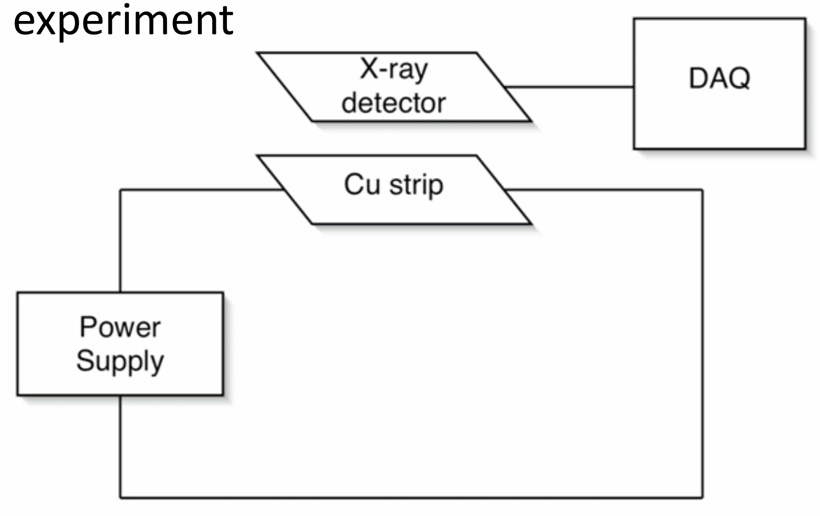
We thank Palash Pal for discussions in the initial stages of this work, Shmuel Nussinov for raising stimulating questions, and George Snow for suggesting the experiment using a current running through a metal. This work was supported in part by the National Science Foundation.

Search for non-Paulian atoms

Search for non-Paulian transitions

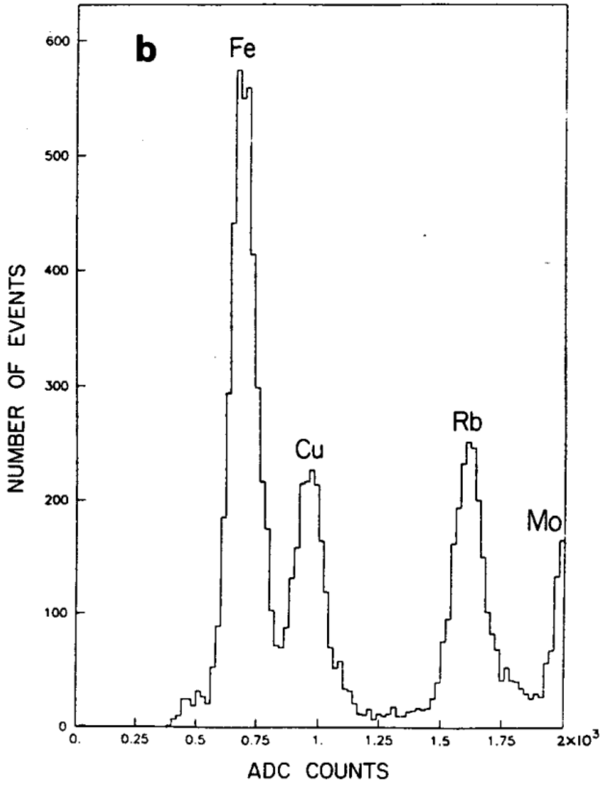
Ramberg & Snow experiment

Instead of a radioactive source a power supply delivers *fresh* electrons to test PEP. Remarkable simple table-top experiment



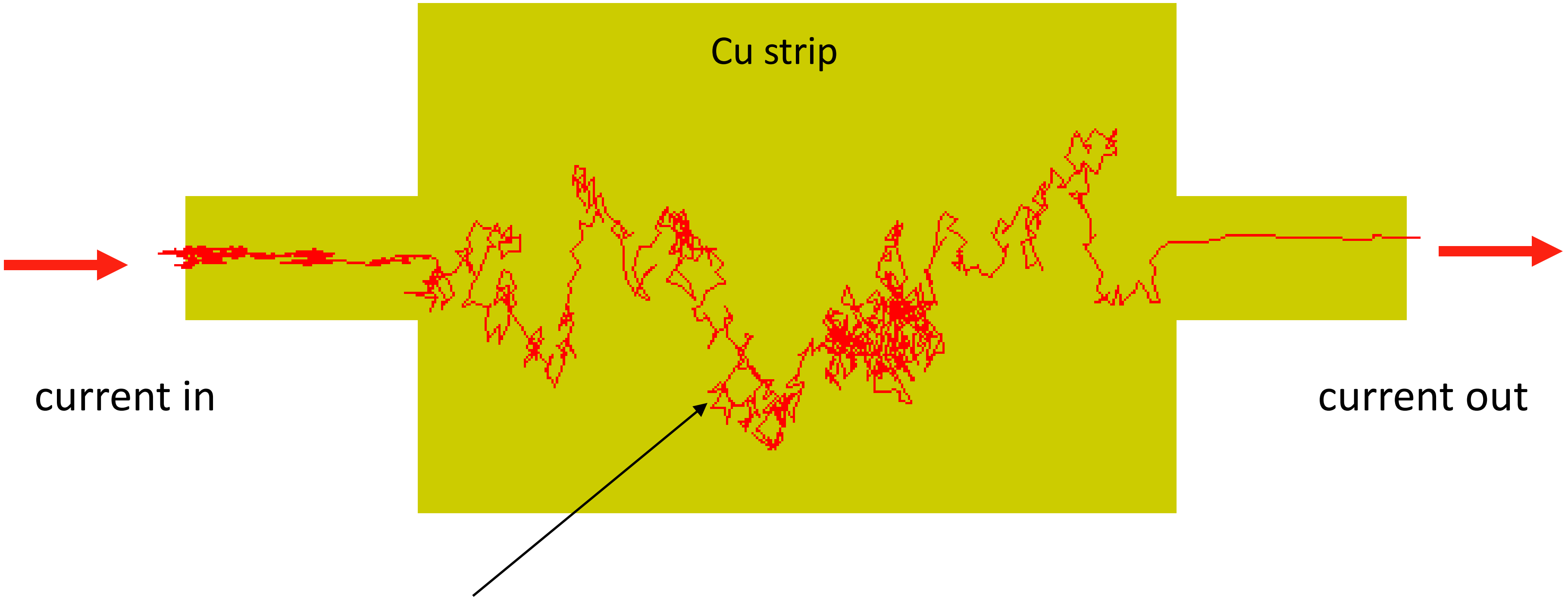
E. Ramberg and G. A. Snow, Phys. Lett. **B238** (1990) 438

X-ray detector:
Closed proportional tube
Detector calibration
$\Delta E \sim 1200$ eV @ 8keV



- **The X-rays detector: proportional tube counter situated above a thin strip of cooper which is connected to a controlled 50A power supply;**
- **Energy resolution of about 1200eV of FWHM at 7keV;**
- **The measurements lasted 2 months; data with and without current were taken, in basement of the Muon building at Fermilab;**
- **Two background runs: one with a piece of cooper that never had current running through it and another where no cooper is present .**

random walk of the conduction electrons in the copper strip



Cu strip

current in

current out

electrons may be captured by copper atoms in the strip

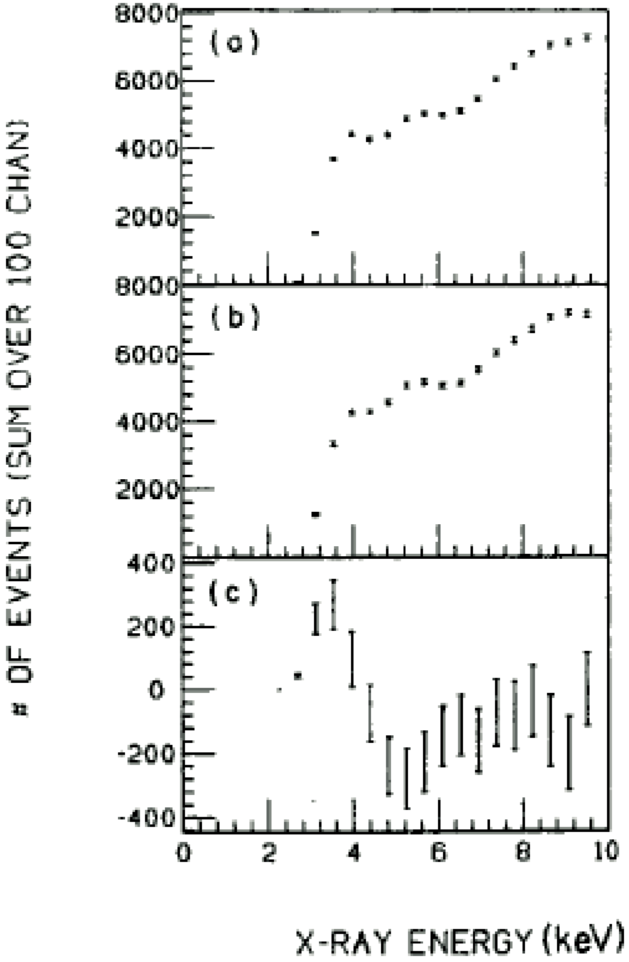


Fig. 2. (a) Number of triggers summed over 100 ADC channels, plotted versus equivalent X-ray energy with current-on in copper strip below X-ray counter. (Note the points are separated by 50 channels, so that only every other point is statistically independent). (b) Same as (a) but with no current passing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

Limit from the Ramberg & Snow Experiment

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

$$= \frac{\beta^2(\Sigma I\Delta t)D}{e\mu\rho z\sigma}$$

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

$$D = 0.025\ m$$

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

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

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

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

$$N_X \geq \beta^2\left(.90\cdot 10^{28}\right), N_X = 3\times 100(3\sigma)$$

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

The Pauli-violating parameter β^2

Ignatiev & Kuzmin model ➡ 3 states connected via creation and destruction operators

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

through the following relations:

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

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

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

http://www.lnf.infn.it/esperimenti/vip

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 violations of the Pauli exclusion principle for the electrons

From:

(Ramberg & Snow -1990)

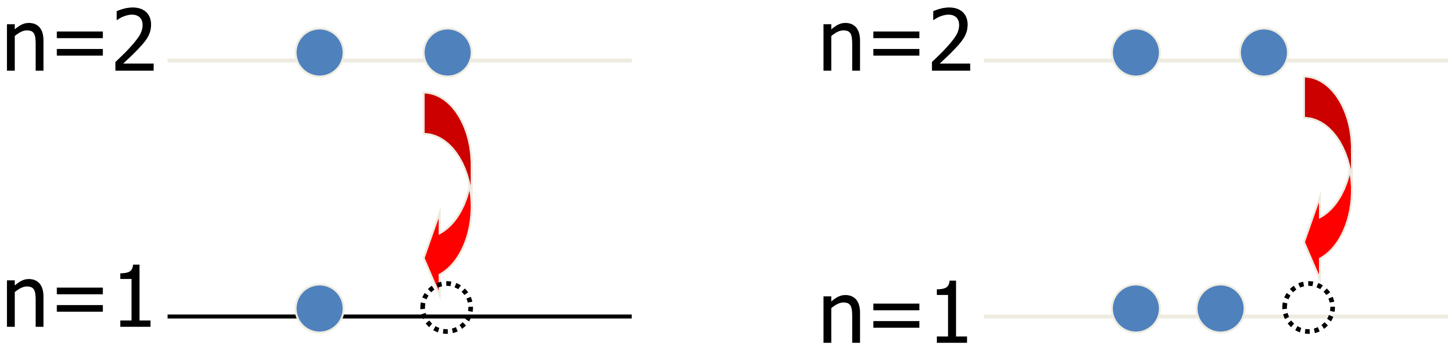
$$\beta^2 / 2 \le 1.7 \cdot 10^{-26} (> 95\% \ \ C.L.)$$

to

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

VIP experimental method

Search for anomalous X-ray transitions



Normal 2p →1s transition

2p →1s transition violating Pauli principle

8.05 keV in Cu

~ 7.7 keV in Cu

Transition energies of anomalous X-rays in Copper

Multiconfiguration Dirac-Fock approach

(including rel. corrections, lamb shift, Breit operator, radiative corrections)

P. Indelicato (Ecole Normale Supérieure et Université Pierre et Marie Curie)

Transition	Initial en.	Final en.	Transition energy (eV)	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 K_α transition in copper: ~ 8040 eV (2p → 1s)

7729eV±10eV

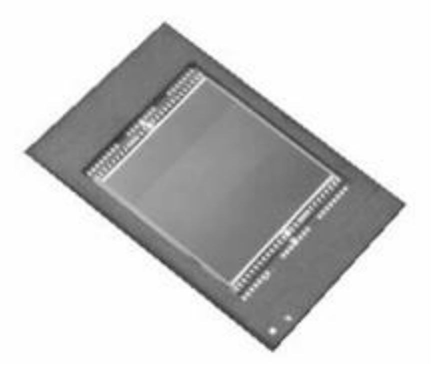
~ 300 eV difference in energy, experimentally resolvable

The VIP experiment

VIP is a substantially improved version of the Ramberg-Snow experiment:

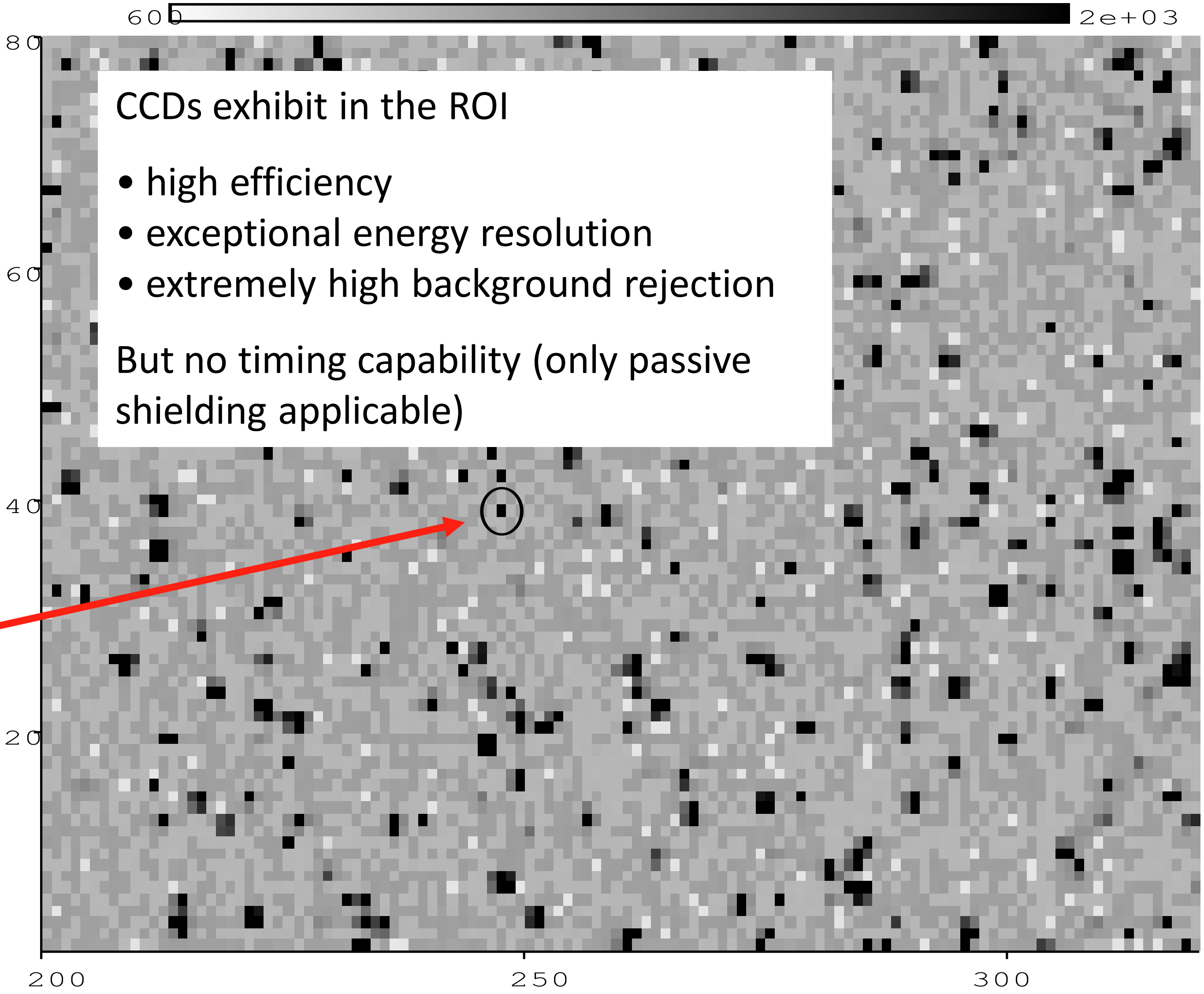
1. large-area, X-ray detectors with high energy resolution and efficiency
2. clean, low-background experimental area (underground lab in Gran Sasso LNGS)
3. large “electron reservoir” (electrons as test particles)

The VIP x-ray detectors: CCD



EEV CCD55

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



CCDs exhibit in the ROI

- high efficiency
- exceptional energy resolution
- extremely high background rejection

But no timing capability (only passive shielding applicable)

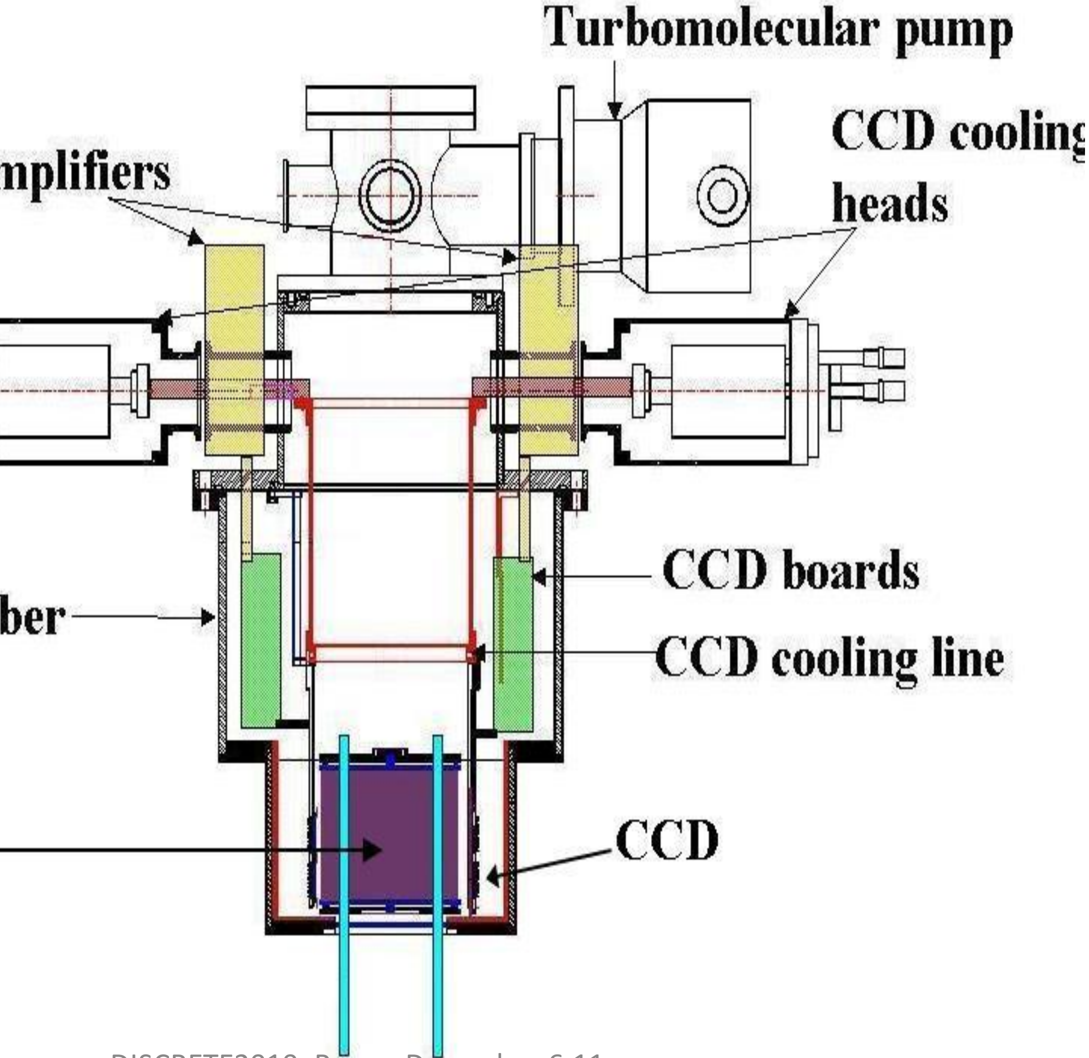
single pixel event,
X-ray photon

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

VIP Experimental activities

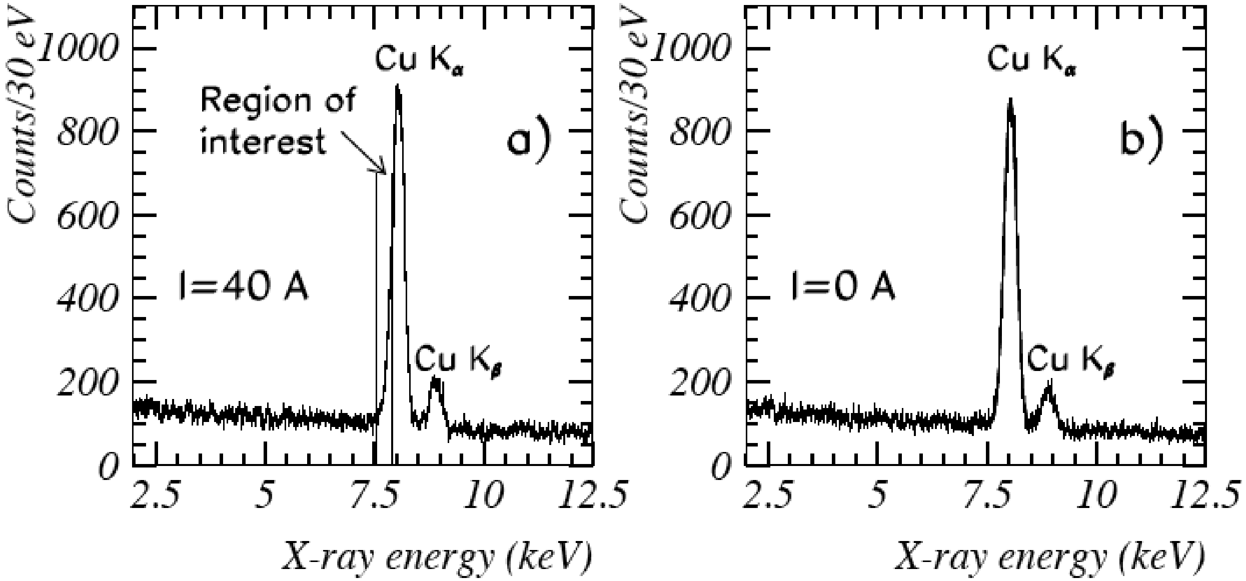
- November-December 2004: measurements with a 2-CCD test setup in the laboratory, with and without shielding;
- End of December 2004: transportation and installation of the test setup setup at LNGS and first tests
- 21 February 2005 – 28 March 2005: 5 weeks of DAQ with shielding with the test setup at 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, with and without current.

The VIP setup

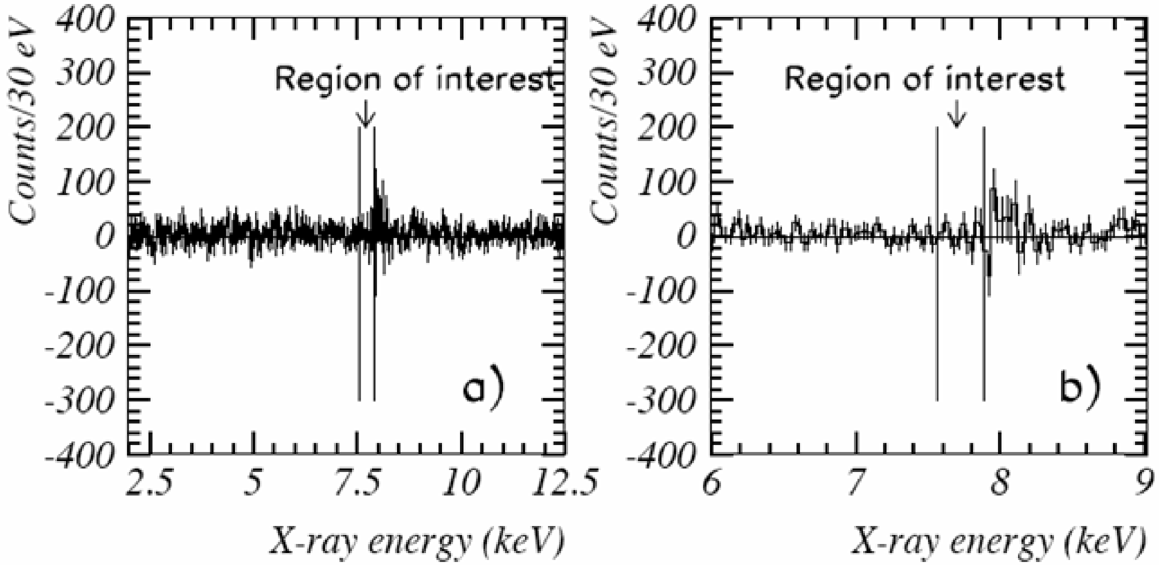


The VIP setup

VIP final setup used for measurements at the LNF-Frascati laboratory



subtracted spectra
("current" - "no current")



VIP first results

@ I=40A → Nx= 2721 ± 52

@ I=0A → Nx= 2742 ± 52

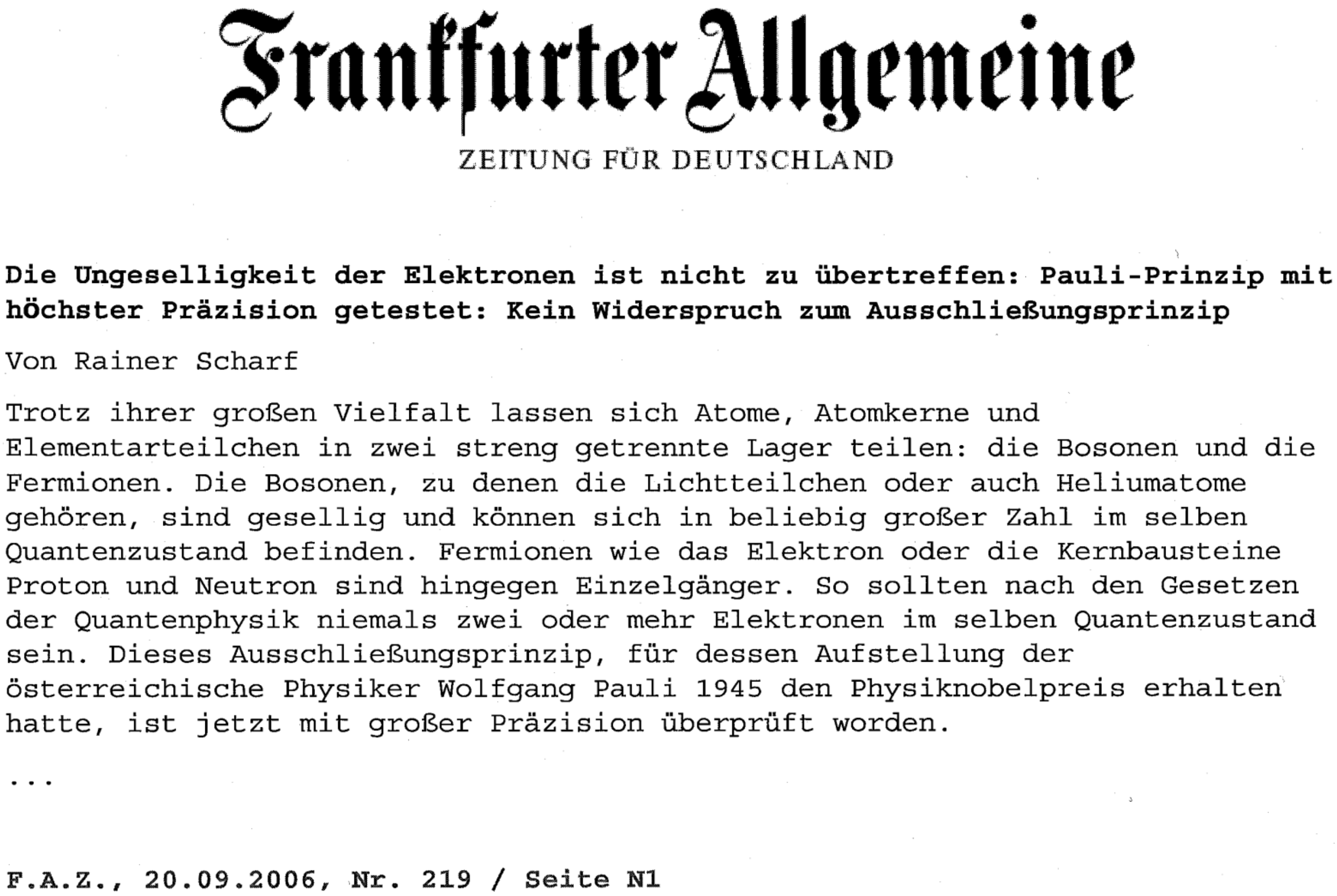
$$N_X \geq 4.9\times10^{29}\cdot\frac{\beta^2}{2}$$

We get for the PEP violating parameter:

$$\boxed{\beta^2/2 \leq 4.5\times10^{-28}\ (99.7\%\ C.L.)}$$

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

Phys. Lett. B 641 (2006) 18



Frankfurter Allgemeine
ZEITUNG FÜR DEUTSCHLAND

Die Ungeselligkeit der Elektronen ist nicht zu übertreffen: Pauli-Prinzip mit hÖchster Präzision getestet: Kein Widerspruch zum Ausschließungsprinzip

Von Rainer Scharf

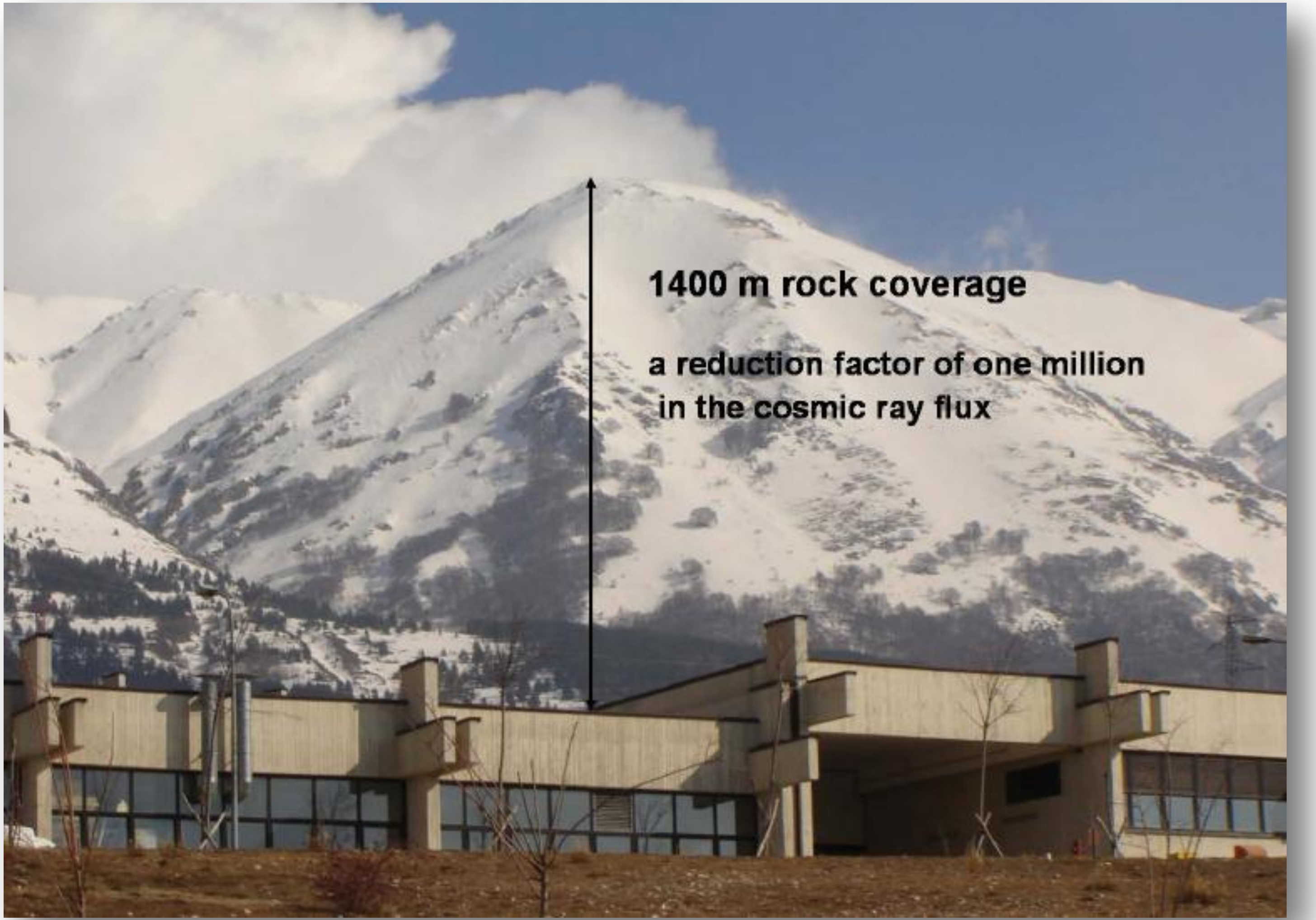
Trotz ihrer großen Vielfalt lassen sich Atome, Atomkerne und Elementarteilchen in zwei streng getrennte Lager teilen: die Bosonen und die Fermionen. Die Bosonen, zu denen die Lichtteilchen oder auch Heliumatome gehören, sind gesellig und können sich in beliebig großer Zahl im selben Quantenzustand befinden. Fermionen wie das Elektron oder die Kernbausteine Proton und Neutron sind hingegen Einzelgänger. So sollten nach den Gesetzen der Quantenphysik niemals zwei oder mehr Elektronen im selben Quantenzustand sein. Dieses Ausschließungsprinzip, für dessen Aufstellung der österreichische Physiker Wolfgang Pauli 1945 den Physiknobelpreis erhalten hatte, ist jetzt mit großer Präzision überprüft worden.

...

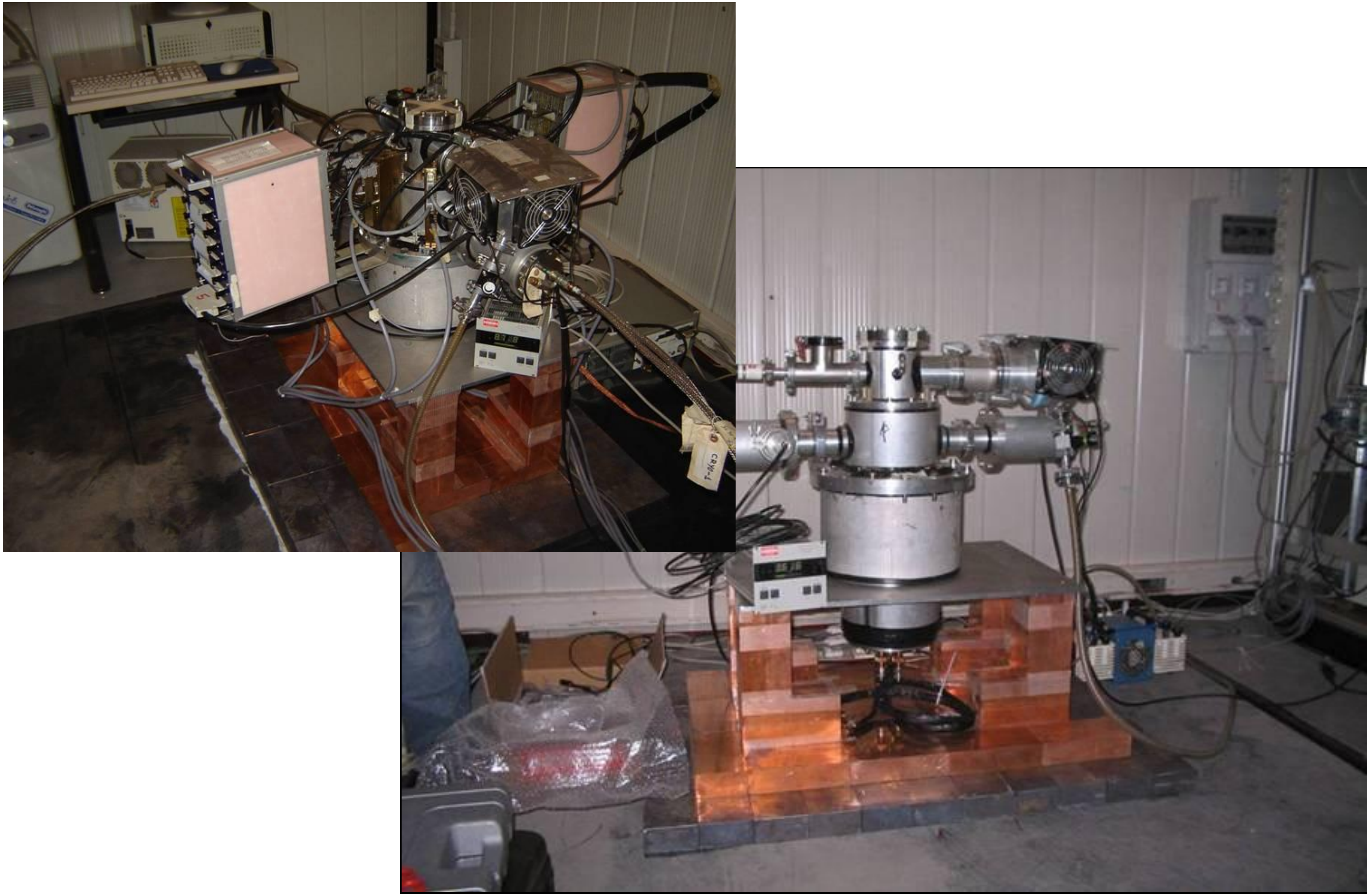
F.A.Z., 20.09.2006, Nr. 219 / Seite N1

Test site and final location:

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


1400 m rock coverage
a reduction factor of one million
in the cosmic ray flux

Final setup at LNGS


5
CRYO-1

Shielding installation


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

VIP-LNGS result

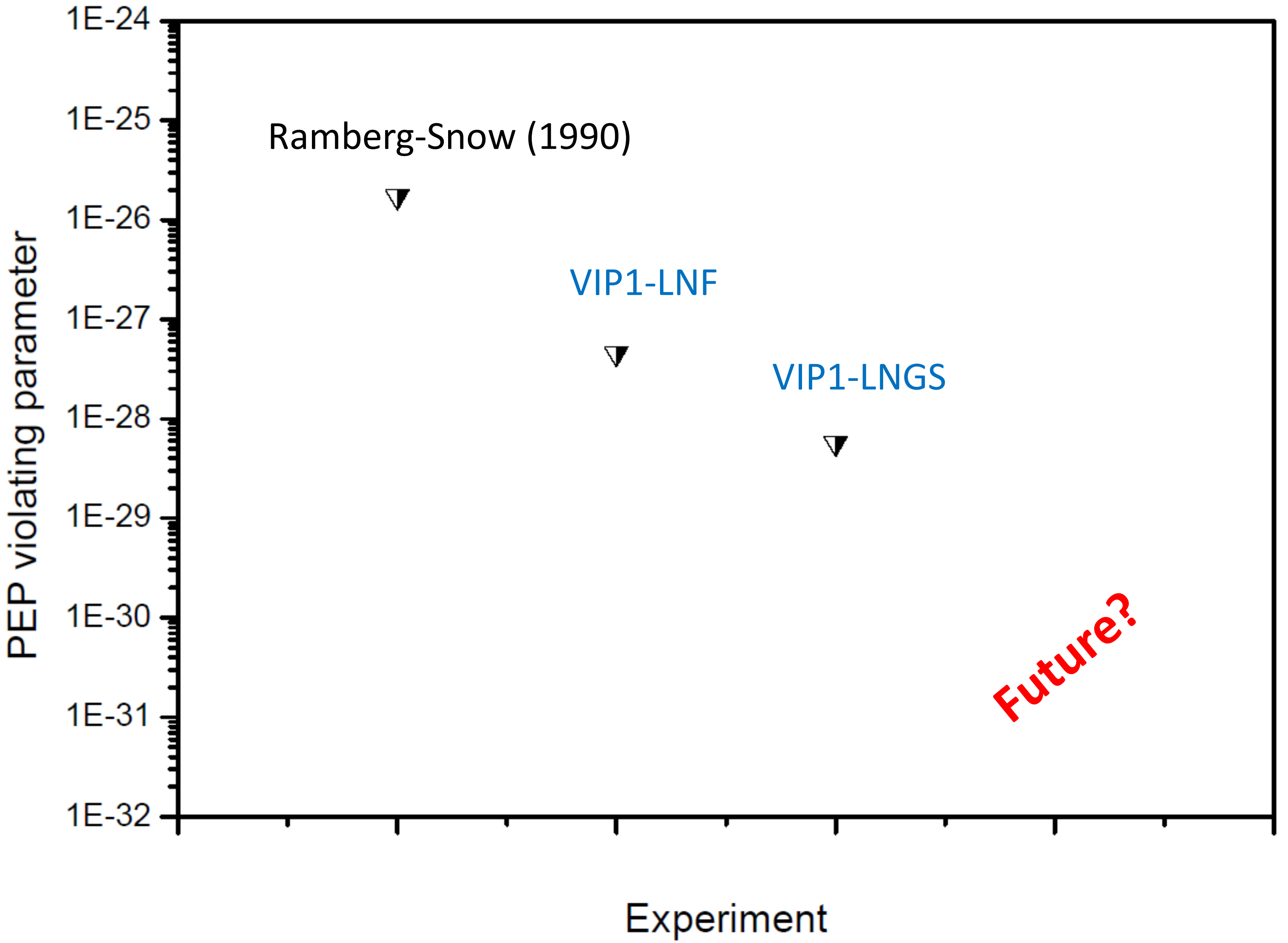
After about 2 years running

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

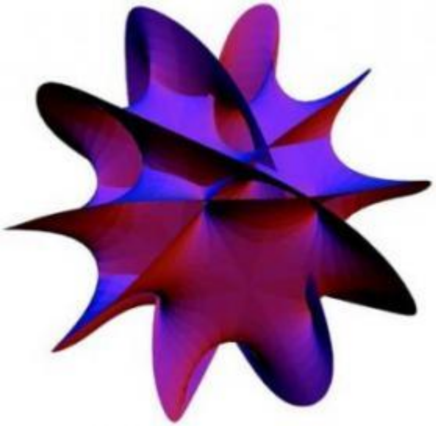
(Preliminary)

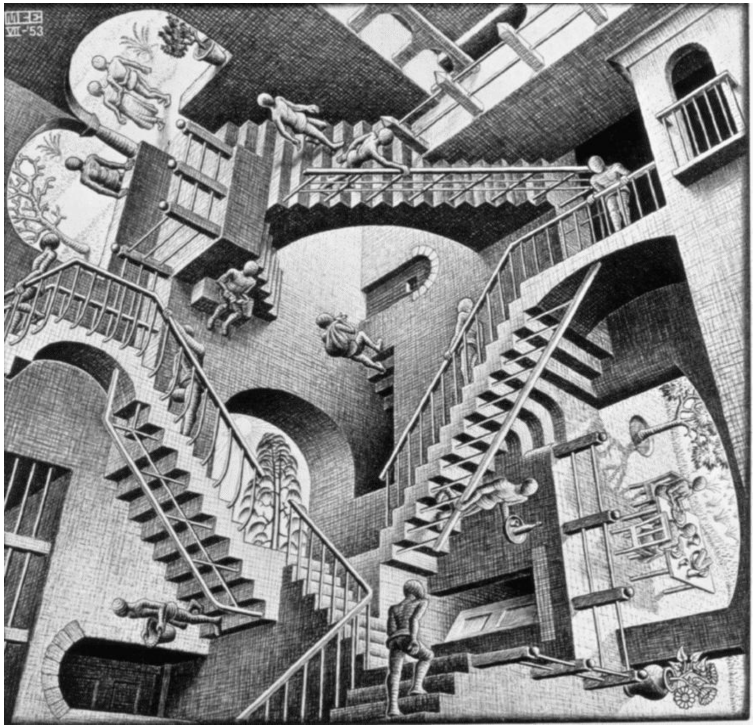
L. Sperandio Ph. D. Thesis, Univ. Roma2, 2008
S. Bartalucci *et al.,* AIP Conf. Proc. 1232, ed. A.Yu. Khrennikov, 206

Progress in sensitivity for direct test with electrons



Interpretation of VIP data





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

There is no acceptable theoretical formalism existing - predicting Pauli principle violation neither for electrons nor for nucleons. Is there a limitation of validity and what is its value? Can it be reached experimentally?

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

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

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

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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 quantum gravity.

Background pictures: Wolfgang Pauli in 1924, approximately at the time he thought about a primitive form of the exclusion principle and on its role in the alkali atom spectra (Photo 11 from the Pauli Archive at CERN, © CERN Copyright, used with permission). The colored lines are a sodium gas emission spectrum.)

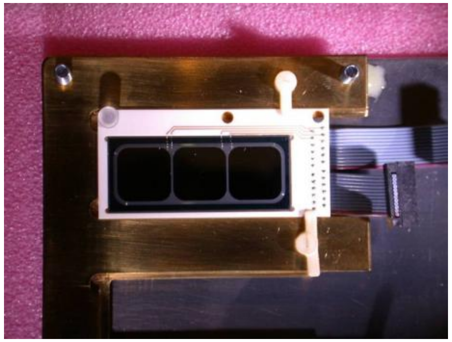
http://www.ts.infn.it/eventi/spinstat2008/home.html
CERN Courier – January-February 2009
Dedicated volume in Foundations of Physics (2010)
Eds.: E. Milotti, C. Curceanu, S. Adler, M. Berry

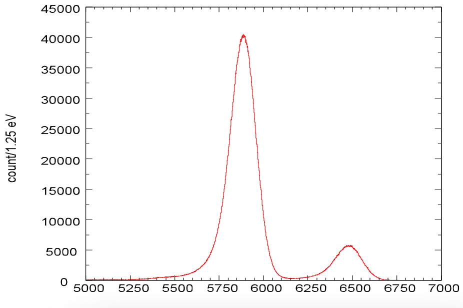
How to increase the sensitivity?

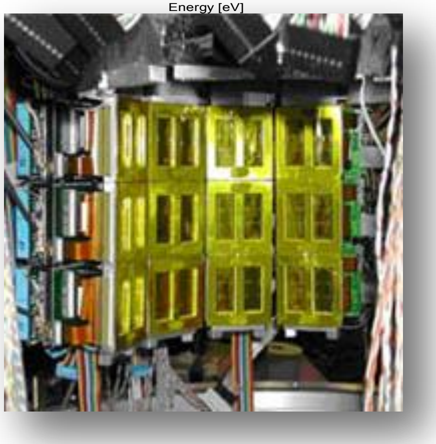
- More „fresh“ electrons – limited by heat dissipation
- Higher x-ray efficiency: increase of detector solid angle
- Reduce background: small efficient detectors
- Optimize shilding: low activity material (inner layer), active shielding

Silicon Drift Detectors (SDDs)

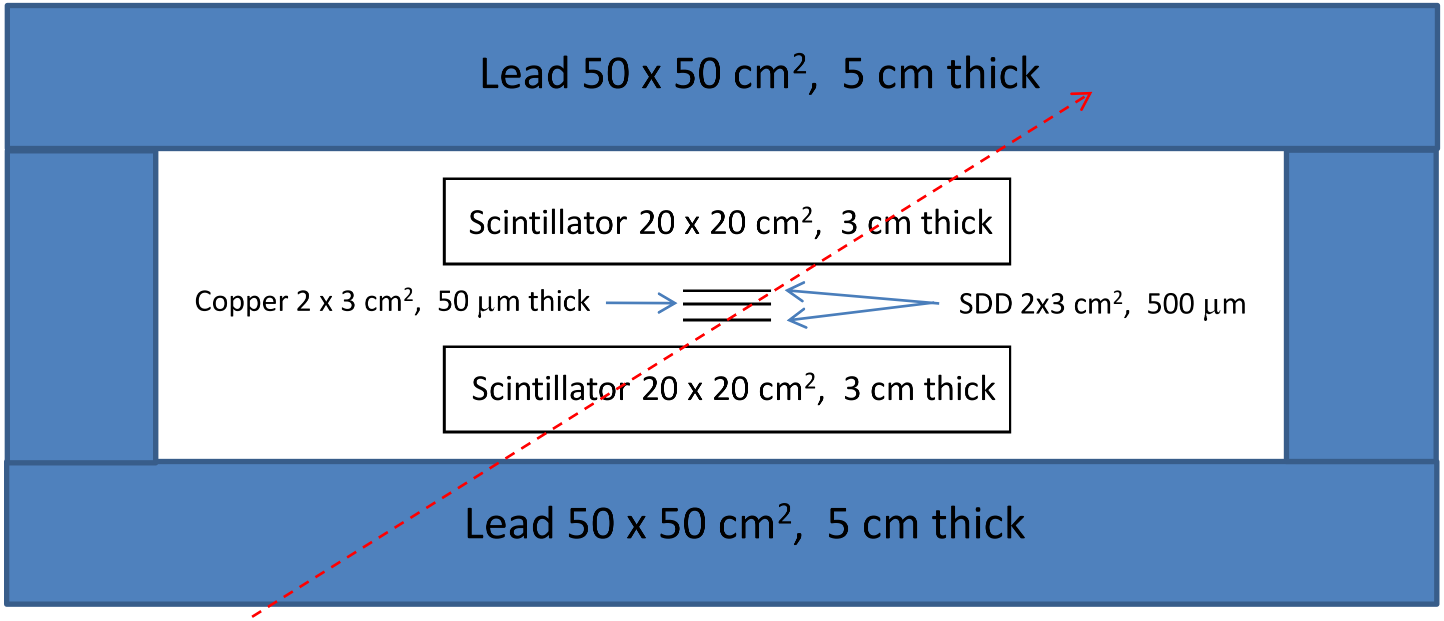
- Large (1 cm^2) SDDs provide excellent energy resolution (even superior than CCDs at 8keV)
- Timing capability for triggering
- Compact design suitable for gaining larger solid angle
- Successfully used in the detection of kaonic atom x-ray spectroscopy at DAFNE (SIDDHARTA), background reduction ~10^4







Background reduction for VIP2 by active shielding



Lead 50 x 50 cm^2, 5 cm thick

Scintillator 20 x 20 cm^2, 3 cm thick

Copper 2 x 3 cm^2, 50 μm thick

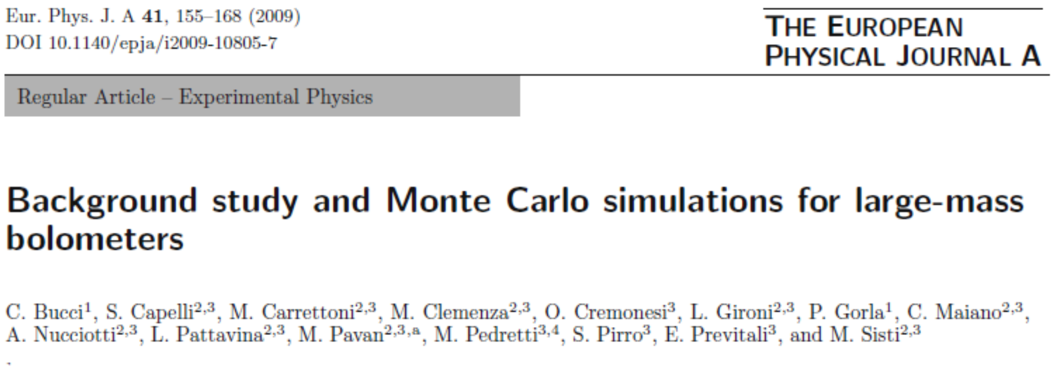
SDD 2x3 cm^2, 500 μm

Scintillator 20 x 20 cm^2, 3 cm thick

Lead 50 x 50 cm^2, 5 cm thick

photon from
environmental
radiation

scheme of a setup with plastic scintillators sandwiching the SDD xray detectors



Eur. Phys. J. A **41**, 155–168 (2009)
DOI 10.1140/epja/i2009-10805-7

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Background study and Monte Carlo simulations for large-mass bolometers

C. Bucci[1], S. Capelli[2,3], M. Carrettoni[2,3], M. Clemenza[2,3], O. Cremonesi[3], L. Gironi[2,3], P. Gorla[1], C. Maiano[2,3], A. Nucciotti[2,3], L. Pattavina[2,3], M. Pavan[2,3,a], M. Pedretti[3,4], S. Pirro[3], E. Previtali[3], and M. Sisti[2,3]

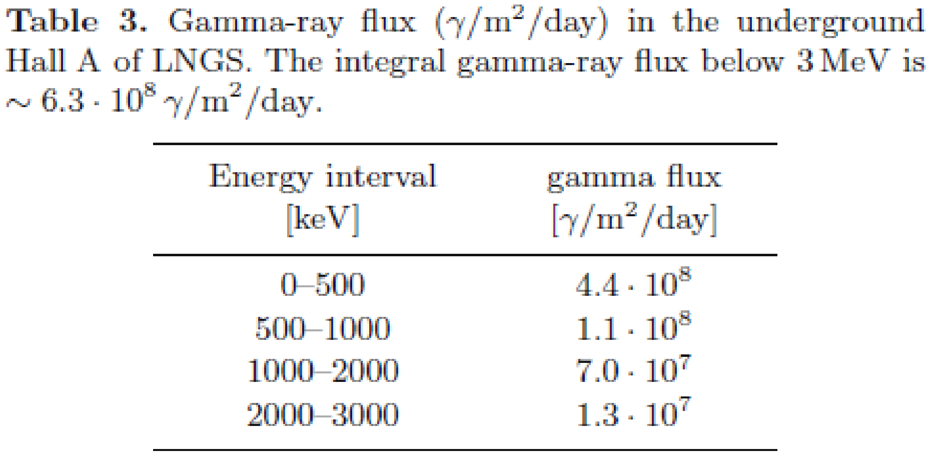


Table 3. Gamma-ray flux ($\gamma/\mathrm{m}^2/\mathrm{day}$) in the underground Hall A of LNGS. The integral gamma-ray flux below 3 MeV is $\sim 6.3 \cdot 10^8\ \gamma/\mathrm{m}^2/\mathrm{day}$.

Energy interval [keV]	gamma flux [$\gamma/\mathrm{m}^2/\mathrm{day}$]
0–500	$4.4 \cdot 10^8$
500–1000	$1.1 \cdot 10^8$
1000–2000	$7.0 \cdot 10^7$
2000–3000	$1.3 \cdot 10^7$

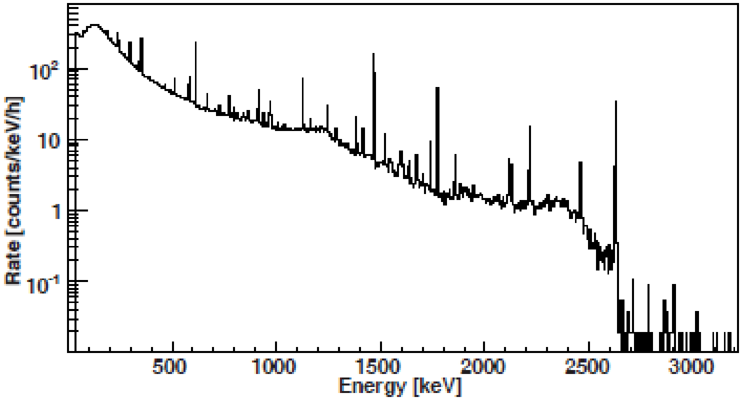
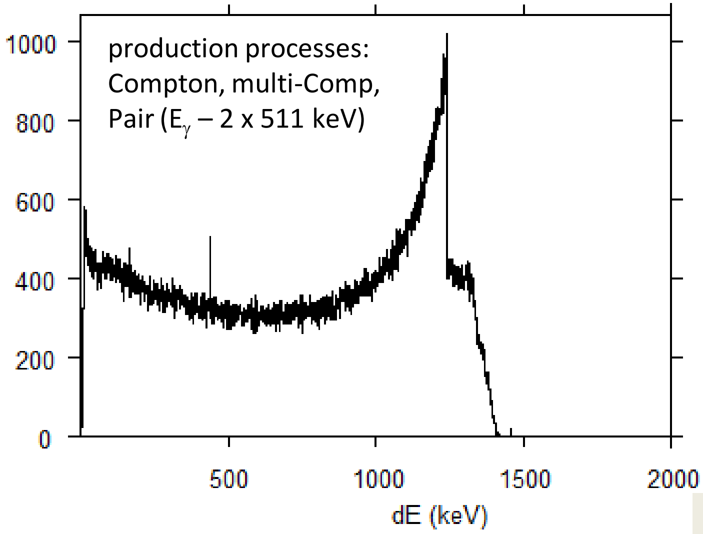
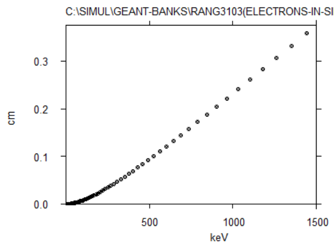


Fig. 1. Gamma-ray spectrum measured at LNGS (Hall A) with a small Ge diode.

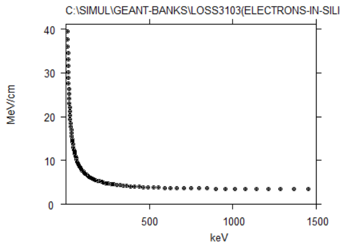
besides the environmental radiation there are still cosmics: Muons at LNGS ~ 1.8 /m^2 /min deposited energy in the scintillators



production processes:
Compton, multi-Comp,
Pair (E_γ – 2 x 511 keV)

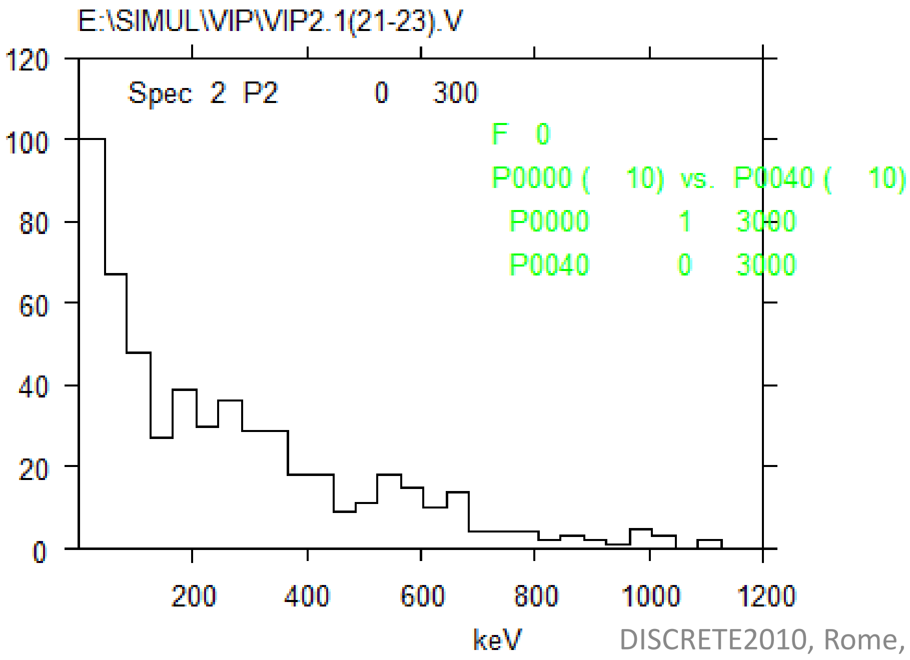


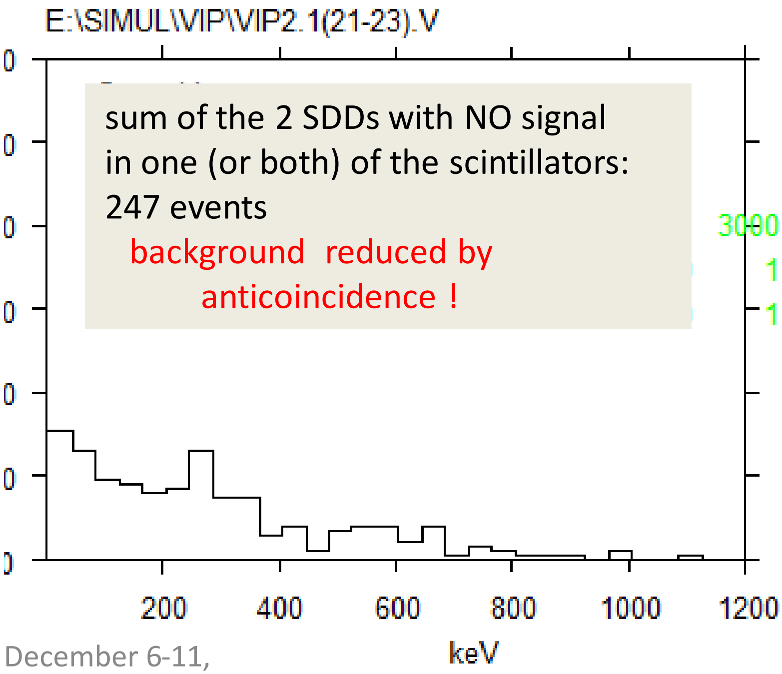
e- in silicon:
range



e- in silicon:
dE/dx

deposited energy in the SDDs

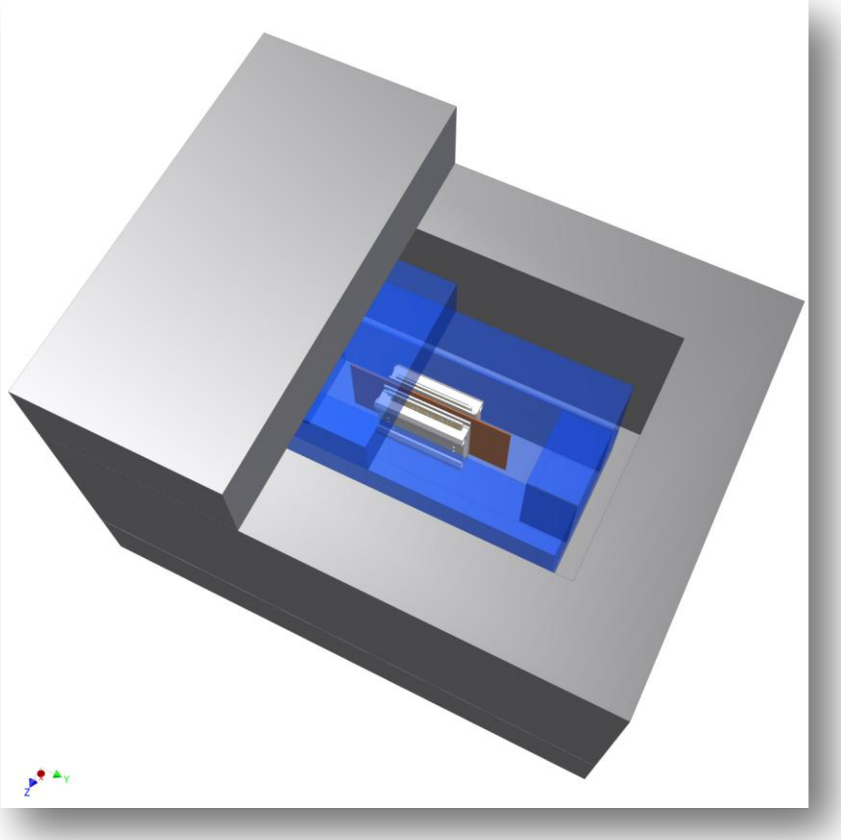


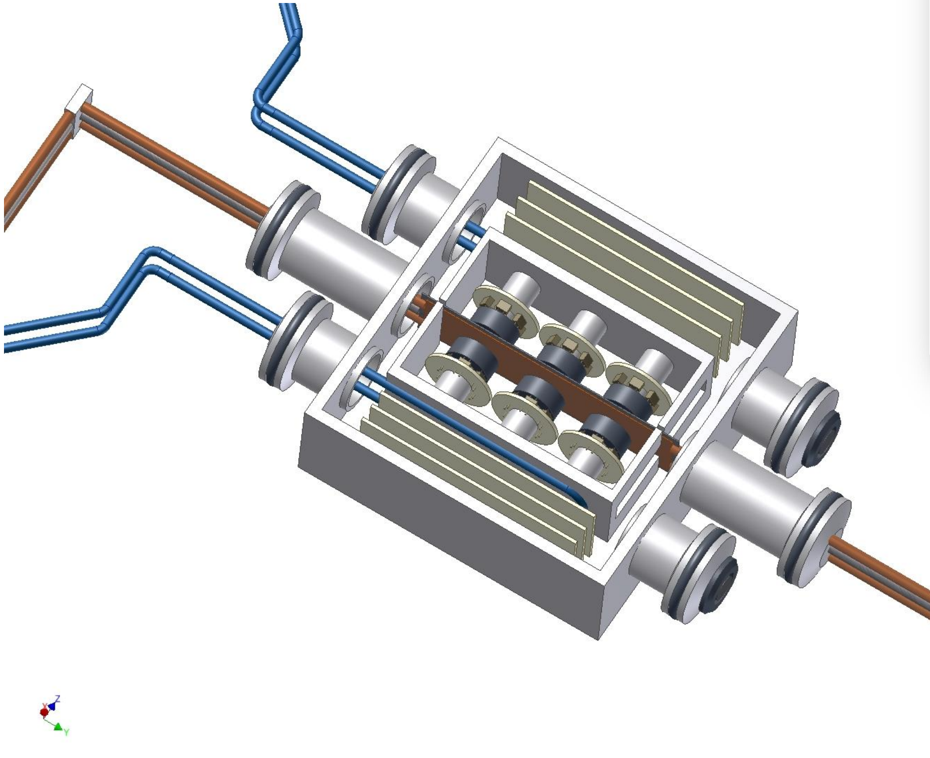


sum of the 2 SDDs with NO signal
in one (or both) of the scintillators:
247 events

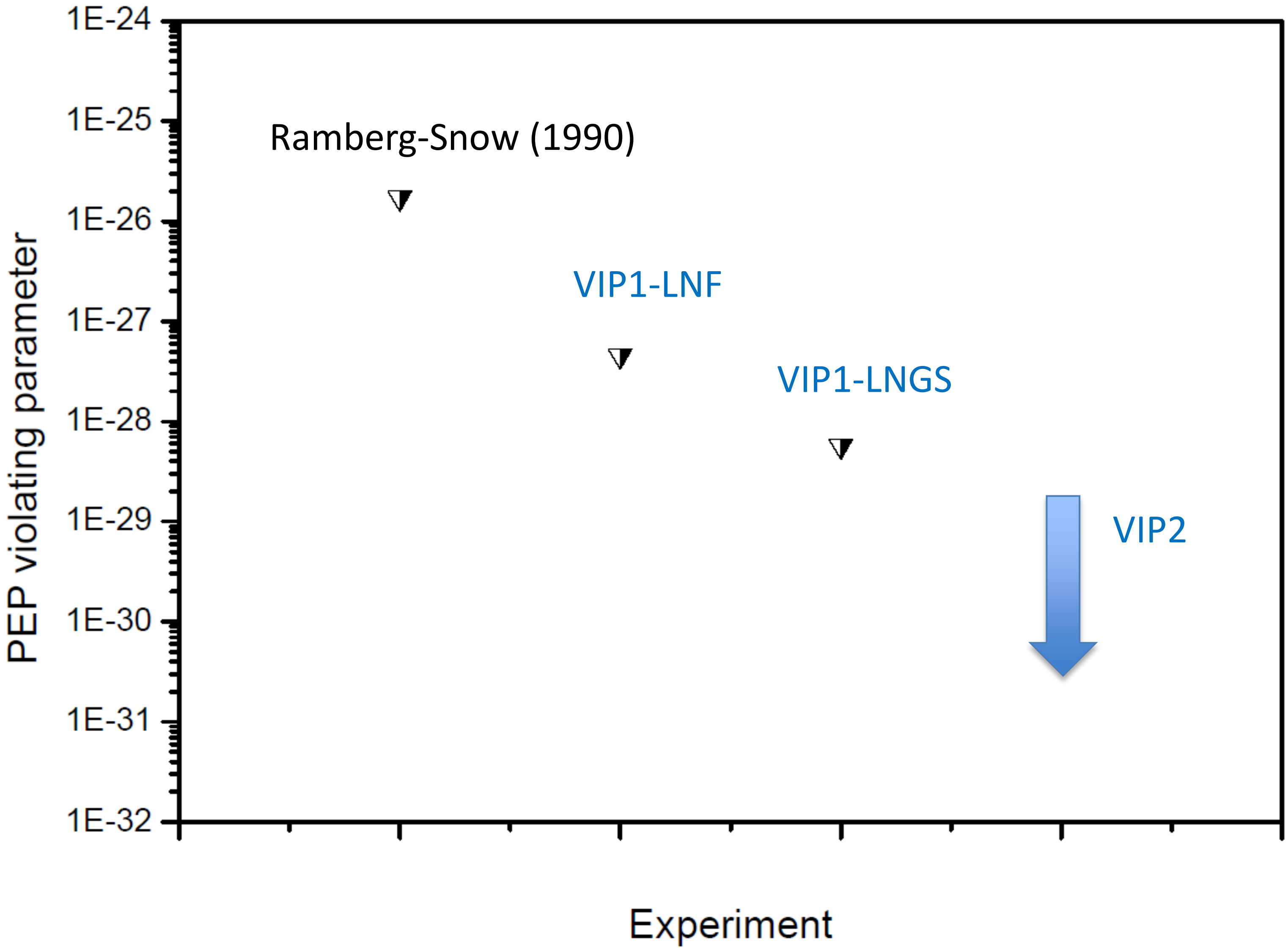
background reduced by
anticoincidence !

With compact VIP2 design
>2 orders of magnitude increase in sensivity



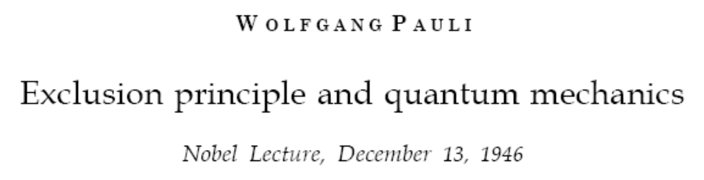


Progress in sensitivity for direct test with electrons



Summary

- Pauli principle – a fundamental rule of nature but difficult to explain in a simple way
- Pauli principle violation can be studied searching for Pauli-forbidden decays with very high sensitivity
- VIP experiment in Gran Sasso set a limit for violation for electrons of about 10^{-29}
- VIP aims at improving the sensitivity by orders of magnitudes (new X-ray detectors, active shielding)



WOLFGANG PAULI

Exclusion principle and quantum mechanics

Nobel Lecture, December 13, 1946

"The history of the exclusion principle is already an old one, but its conclusion has not yet been written".

This is why Pauli's principle still keeps physicists searching for a deeper understanding

If something in fundamental physics can be tested, then it absolutely must be tested (Okun)

Thank you for your attention!

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

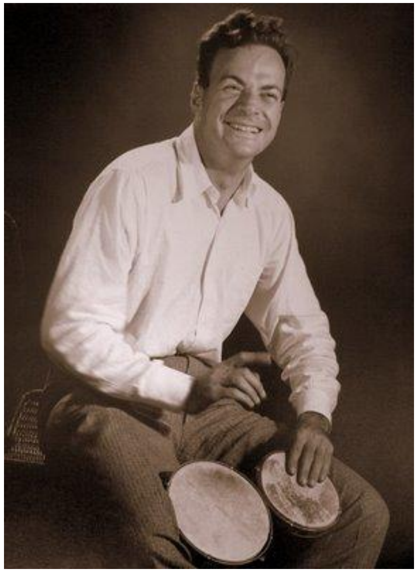
Postulates:

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

Feynman Lectures on Physics



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, <u>but we have not been able to find a way to reproduce his arguments on an elementary level</u>. 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

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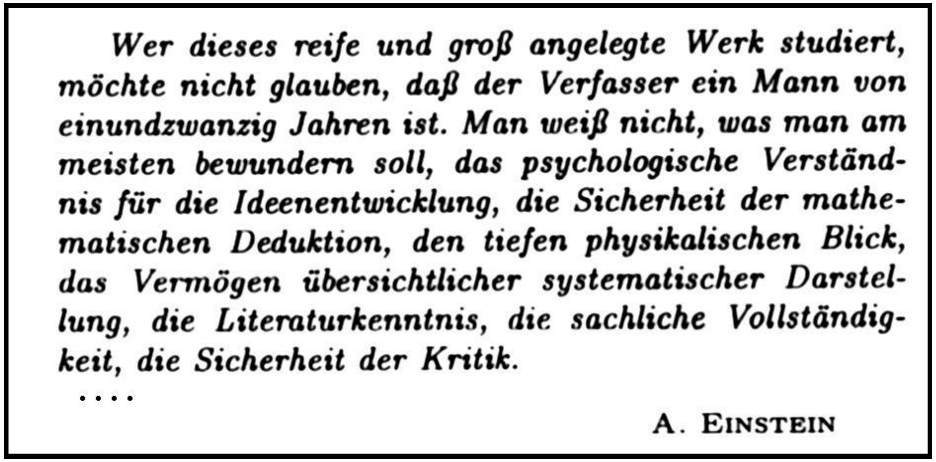
Pauli as genius



Wer dieses reife und groß angelegte Werk studiert, möchte nicht glauben, daß der Verfasser ein Mann von einundzwanzig Jahren ist. Man weiß nicht, was man am meisten bewundern soll, das psychologische Verständnis für die Ideenentwicklung, die Sicherheit der mathematischen Deduktion, den tiefen physikalischen Blick, das Vermögen übersichtlicher systematischer Darstellung, die Literaturkenntnis, die sachliche Vollständigkeit, die Sicherheit der Kritik.

....

A. EINSTEIN

At the age of 20 he wrote as student of Sommerfeld a work on the theory of relativity.