New experimental limit on the Pauli exclusion principle violation by electrons

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LNF INFN

QUANTUM MECHANICS: FROM FUNDAMENTAL PROBLEMS TO APPLICATIONS - Bertinoro (Italy), December 4-7, 2006

Outline of Part I

1. The Pauli Exclusion Principle (PEP)
   - Violation of PEP for electrons
   - Theoretical model; The β parameter

Outline of Part II

2 Experimental search for a possible PEP violation

- Numerical calculus of ′anomalous′ transition
- Experimental calculation of $\frac{\beta^2}{2}$

3 Structure and characteristics of the detector

- High resolution detector

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   - High resolution detector

Outline of Part III

4 **Experimental activities and results**
- Experimental results in LNF
- Experimental results in LNGS

Part I

Theoretical aspects

Outline

1. **The Pauli Exclusion Principle (PEP)**
   - Violation of PEP for electrons
   - Theoretical model; The β parameter

The Pauli Exclusion Principle (PEP).

- 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.
- But 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.

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The Pauli Exclusion Principle (PEP).

- 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.
- Significant papers on the PEP violation

1. E. Fermi, Atti. Sci. It. Prog. Sci. 22 Riunione (Bari 1933), vol. 3, p.7; E. Fermi, Scientia 55, 21 (1934)
2. P. A. M Dirac, The Principles of Quantum Mechanics (Clarendon Press, Oxford, 1958), Chapter IX
3. W. Pauli, Die Allgemeihen Prinzipen der Wellenmechanik, in Handbuch der Physik (Springer-Verlag, Berlin, 1958), Bd. 5, T.1, Sect. 14
4. V. L. Luboshitz and M. I. Podgoretskii, Sov. Phys. JETP 33, 5 (1971)
5. R. D. Amado and H. Primakoff, Phys. Rev. C22, 1338 (1980)
6. A. Yu. Ignatiev and V. A. Kuzmin, Yad. Fiz 46, 786(1987) (Sov. J. Nucl. Phys.)
7. O. W. Greenberg and R. N. Mohapatra, Phys. Rev. Lett. 59, 2507 (1987)
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Violating theory for electrons

In a principle-violating theory, a pair of electrons in a mixed state has the probability $\frac{\beta^2}{2}$ for the symmetric component and $(1 - \frac{\beta^2}{2})$ for the usual antisymmetric component.

A. Yu. Ignatiev and V. A. Kuzmin, Yad. Fiz 46, 786(1987) (Sov. J. Nucl. Phys.)
O. W. Greenberg and R. N. Mohapatra, Phys. Rev. Lett. 59, 2507 (1987)

Goal of VIP

The VIP experiment has the scientific goal of reducing by four orders of magnitude the limit on the probability of a possible violations of the Pauli exclusion principle for the electrons obtained in the Ramberg Snow experiment.

from...

$$\frac{1}{2}\beta^2 \leq 1.7 \times 10^{-26}$$

Ramberg Snow Phys. Lett. B238 (1990) 438

...to

$$\frac{1}{2}\beta^2 \leq 10^{-30}$$

Ignatiev and 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 $|2\rangle$.

We would like to stress that the small PEP violation is an intuitive concept and one can try to formalize it in many different ways leading to different theories with their specific experimental predictions.

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Ignatiev and Kuzmin model.

Creation and destruction operators connect 3 states

$$a^\dagger \sim \begin{pmatrix} 0 & \beta & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}; \quad a \sim \begin{pmatrix} 0 & 0 & 0 \\ \beta & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix};$$

$$a_F^\dagger \sim \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}; \quad a_F \sim \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}.$$

according with their actions:

$$\begin{aligned} a^\dagger|0\rangle &= |1\rangle; \quad a|0\rangle = |0\rangle \\ a^\dagger|1\rangle &= \beta|2\rangle; \quad a|1\rangle = |0\rangle \\ a^\dagger|2\rangle &= |0\rangle; \quad a|2\rangle = \beta|1\rangle \end{aligned}$$

When $\beta = 0$ we regain the standard Fermi-Dirac statistic.

Ignatiev and Kuzmin model.

No bilinear commutation relations, however there are nontrivial trilinear relations between creation and annihilation operators

$$
\begin{aligned}
a^2 a^\dagger + \beta^2 a^{\dagger 2} &= \beta^2 a; \\
a^2 a^\dagger + \beta^4 a^{\dagger 2} &= \beta^2 a a^\dagger a;
\end{aligned}
$$

Ignatiev and Kuzmin model.

- These new matrices describe **one level** wich can be either empty or filled by one electron, or, with the small amplitude β filled by two electrons;
- The generalization to **infinite numbers of levels** was done by O. W. Greenberg and R. N. Mohapatra and by L. B. Okun.

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- ***In spite of the fact that at the present we have no theoretical self consistent framework for a description of violation of charge conservation and/or the exclusion principle , I do not think that experimentalist should stop testing these fundamental concepts of modern physics. In fundamental physics if something can be tested it should be tested.***

  L.Okun, Comments On Nuclear and Particle Physics, 1989, Vol. 19, No. 3, pp. 99-116

- ***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..***

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Part II

Experimental methods and VIP setup

Outline

2. **Experimental search for a possible PEP violation**
   - Numerical calculus of ′anomalous′ transition
   - Experimental calculation of $\frac{\beta^2}{2}$

3. **Structure and characteristics of the detector**
   - High resolution detector

How to search experimentally for a possible violation of PEP for electrons

- Search for atoms or nuclei in ground state which are prohibited by normal statistics;
- Search for transitions which are prohibited by normal statistics

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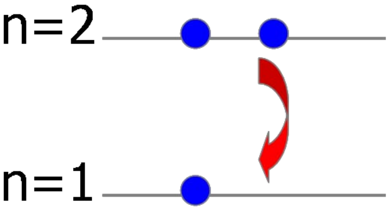
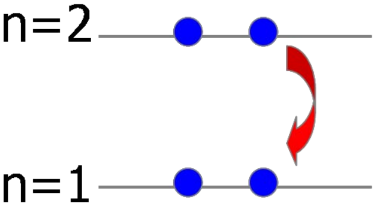
Transition energies of the anomalous X-rays in Copper



Normal $2p \rightarrow 1s$ transition;
8.05 keV in Cu



$2p \rightarrow 1s$ transition violating Pauli principle;
7.7 keV in Cu

Multiconfiguration Dirac-Fock approach

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

Transition	Initial en.	Final en.	Transition	Radiative transition energy	Multipole order rate (s-1)
2p1/2 - 1s1/2	-45799	-53528	7729	2.63E+14	E1
2p3/2 - 1s1/2	-45780	-53528	7748	2.56E+14	E1+M2
3p1/2 - 1s1/2	-44998	-53528	8530	2.78E+13	E1
3p3/2 - 1s1/2	-44996	-53528	8532	2.68E+13	E1+M2

The uncertainty on these values is around several eV.

Multiconfiguration Dirac-Fock approach

Software for muonic atoms which take into consideration:

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

Energy of the anomalous transitions

$$7729\text{eV} \pm 10\text{eV}$$

"New" electrons

- Search for anomalous electronic transitions in Cu (7.7 keV instead of 8.04 keV) induced by a circulating current ('new' external electrons, which interact with the valence electrons), namely transition from 2p to 1s already filled by 2 electrons.
- When a 'new' electron scatters for a normal atom, the electrons can rearrange and a Pauli-violating ('anomalous') state can appear with a probability of order $\frac{\beta^2}{2}$ compared to the Pauli-conserving (normal) state . This state will be an excited state which will then decay to an anomalous ground state, emitting Auger electrons for low Z or X rays for high Z.

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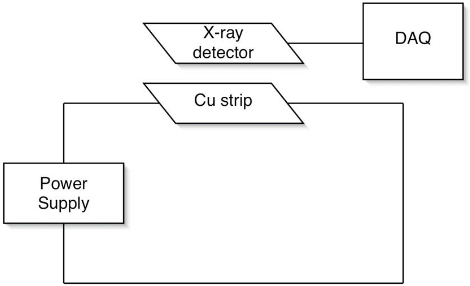
Ramberg and Snow experiment



- **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 .**

How to determine experimental limit on

The experimental limit is a function of:

- **Number of new electrons;**

$$N_{new} = (1/e)\Sigma I \Delta t$$

- **Number of scatters just below (in front of) the detector;**

$$N_{int} = \frac{diameter}{m.f.p} = \frac{D}{\mu}$$

- **Expected number of X-rays N_X;**
- **Geometric factor ;**

$$GF = \frac{\pi\lambda}{8z} = \frac{\pi}{8\rho\sigma}$$

- **the capture probability was asumed to be greater than $\frac{1}{10}$ scatter probability.**

The relation on the limit of violation probability

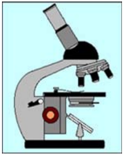
$$N_X \geq \frac{1}{2}\beta^2 N_{new} \frac{1}{10} N_{int} \times (geometricfactor)$$
$$= \frac{\beta^2(\Sigma I \Delta t)D}{e\mu} \frac{1}{20} \times (geometricfactor)$$

Outline

VIP experiment

VIP is a dedicated experiment for the measurements of the violation probability of the Pauli Exclusion Principle for electrons which use the same methods like Ramberg and Snow experiment, but with an higher sensitivity apparatus.

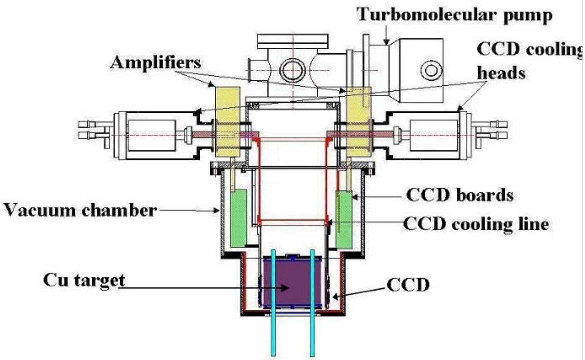
Ramberg and Snow experiment



VIP experiment

Characteristics of the detector

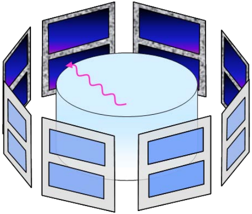
The VIP setup equipped with 16 CCDs (general layout)

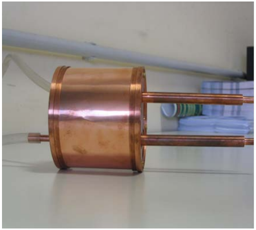


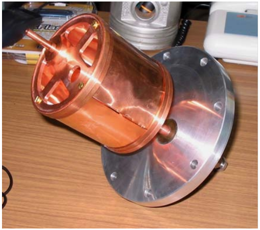
The VIP setup equipped with 16 CCDs
Cu target

VIP Cu target cylinder:

- Radius: 4.5 cm;
- Thick: 50 μm;
- Length: 8.8 cm;





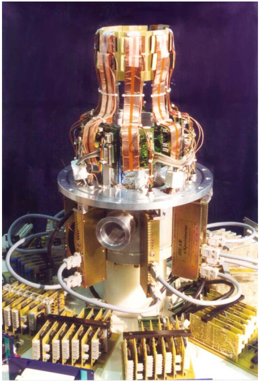


The CCD detectors are at a distance of 2.3 cm from Cu cylinder.

Characteristics of the detector

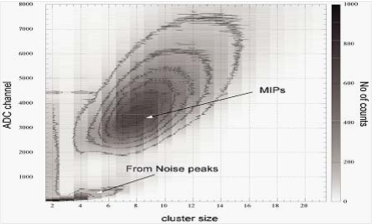
The VIP setup equipped with 16 CCDs
CCD Detector

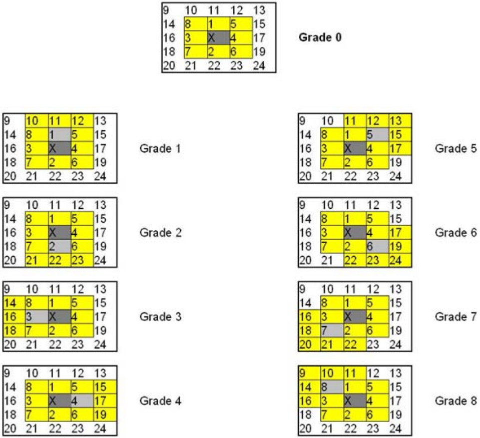
- **16 CCD-55 Charged Coupled Devices chips Marconi Applied Technologies, CCD55-30;**
- **are designed for low temperature operation ($\backsim 150K$), to minimize the thermal noise ;**
- **1242rows x 1152columns=1430784** *pixels*
  a pixel size of 22.5x22.5 *mm*
  an effective area of 7.3 cm^2 **;**
- **The CCD detectors are at a distance of 2.3 cm from Cu cylinder.**



The VIP setup equipped with 16 CCDs (pixel selection criteria)

- **Best detectors for soft X-rays(1-20keV) in terms of background rejection (60% at 6keV), based on pattern recognition and resolution (320eV at 7keV);**
- **Able to measure accurately the energy deposited by a single photon.**





Part III

Experimental activities and results

Outline

4 **Experimental activities and results**

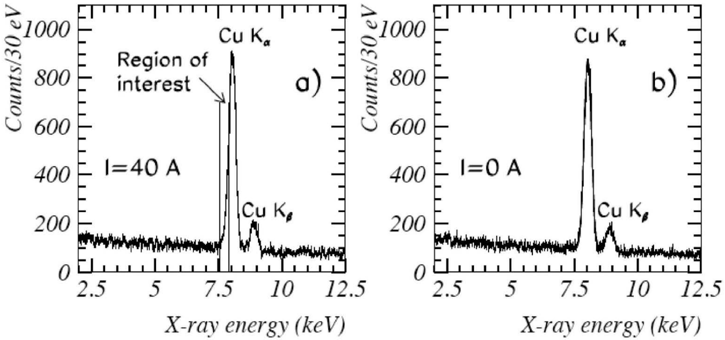
- Experimental results in LNF
- Experimental results in LNGS

Experimental activities since October 2004

- 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 measurements (without shielding);
- 21 February 2005 28 March 2005: 5 weeks of DAQ with shielding with the test setup at LNGS;
- 21 November 13 December 2005: 3 weeks of DAQ with the whole setup without shielding at LNF;
- February 2006: transportation and installation of the definitive VIP setup at LNGS and first measurements without shielding;
- March 2006: installation of the final shielding for the VIP setup and start DAQ for 2 years measurements, with and without current.

VIP setup in LNF laboratory

Energy spectra for the VIP measurements with the VIP setup in LNF



14510 minutes (about 10 days) of measurements for each type of measurement (with and without circulating current).

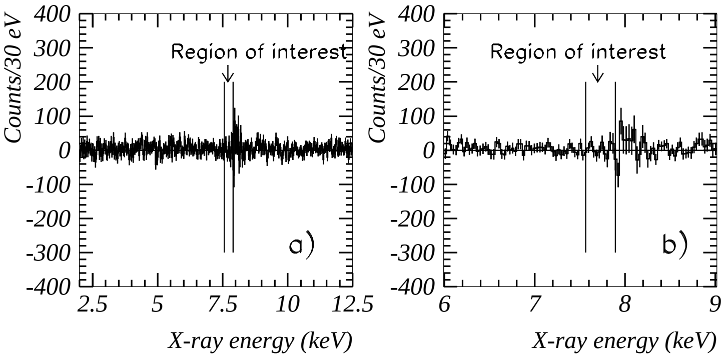
The ′region of interest′

- Energy of the anomalous transitions
- Resolution of VIP setup for 7keV

$$\Downarrow$$

7729eV-160eV-5eV, 7729eV+160eV+5eV

The subtracted spectrum: current minus no-current



In order to evaluate the X-ray due to the possible PEP violating transitions, the spectrum without current was subtracted from the one with current.

The new PEP violation probability limit

In the region of interest were found:

- **for I = 40 A: N_X = 2721$\pm$ 52;**
- **for I =0 A: N_X = 2742$\pm$52;**
- **for the substracted spectrum: ΔN_X =-21$\pm$ 73.**

$\Sigma I \Delta t = 34.824 \times 10^6$ **C,** $D = 8.8$ **cm,** $\mu = 3.9 \times 10^{-6}$ **cm,** $e = 1.602 \times 10^{-19}$ **C and a** ***geometric factor*** **evaluated with a simulation MonteCarlo to be** 1% **it will results:**

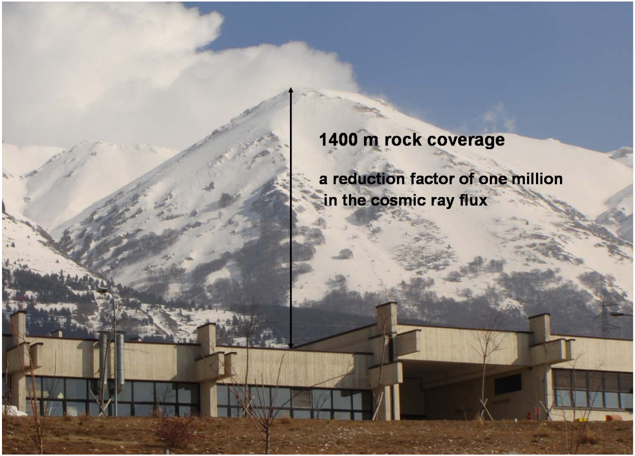
$$N_X \geq 4.9 \times 10^{29} \times \frac{\beta^2}{2}.$$

Taking as a limit of observation three standard deviations, for the difference of events between the measurements with and without current we get for β :

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

Phys. Lett. B 641, 18 (2006)

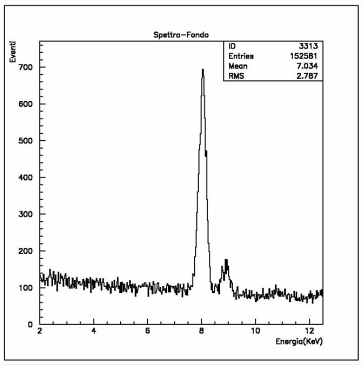
Gran Sasso underground laboratory

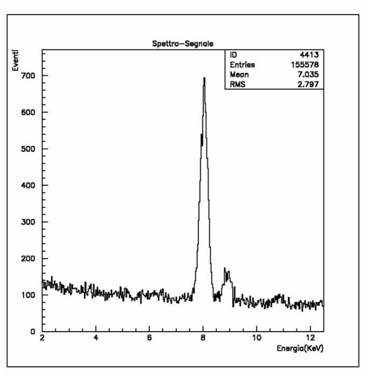


It is the largest underground laboratory in the world for experiments in particle physics and nuclear astrophysics. It is used as a worldwide facility by scientists, presently 750 in number, from 22 different countries, working at about 15 experiments in their different phases .

VIP in Gran Sasso underground laboratory

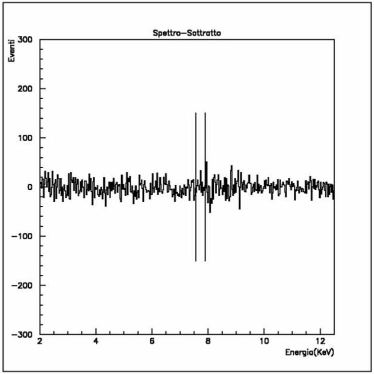
Energy spectra for the VIP measurements with the VIP setup in LNGS

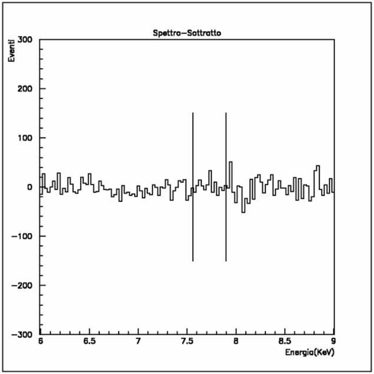




20895 minutes of measurements for each type of measurement (with and without circulating current).

The subtracted spectrum: current minus no-current





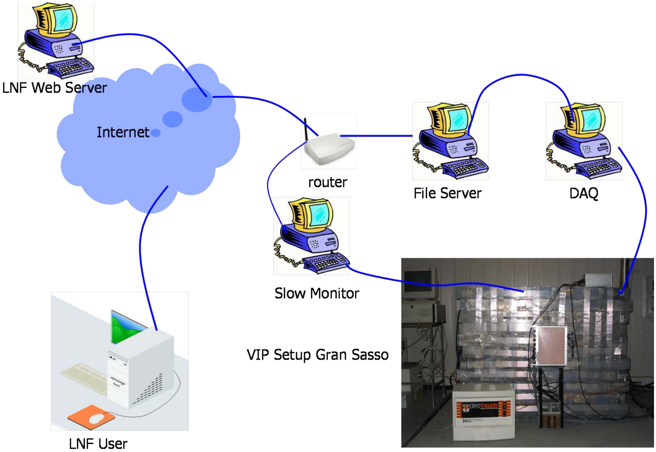
The new limit

$$\frac{\beta^2}{2} \leq 2.9 \times 10^{-28}$$

The shielding

The shielding

SlowControl system



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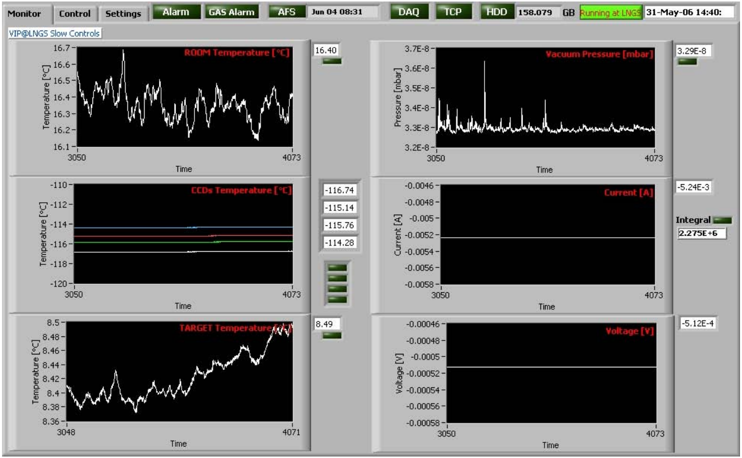
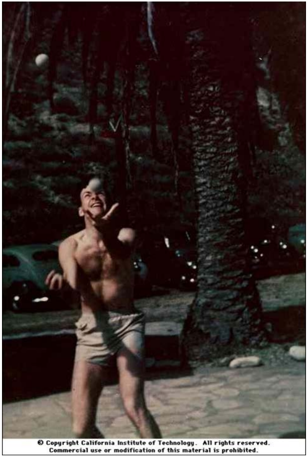


Conclusion and Perspectives

- This year VIP improved the experimental limit of the probability of PEP violation by electrons with a factor of 40;
- The VIP measurement will contiune until the end of 2007 in the Gran Sasso-INFN underground laboratory, for bringing the limit of violation of the Pauli principle for electrons into the 10^{-30} region, which is of particular interest, for all those theories related to the possible PEP violation coming from new physics.

Again Pauli Exclusion Principle



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.

Thank you!

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