VIP Experiment: the experimental limit on Pauli Exclusion Principle violation by electrons

D. Pietreanu

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

Trieste, Italy - October 21 - 25, 2008

The VIP Collaboration

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  STEFAN MEYER Institute for Subatomic Physics, Vienna, Austria

1. **The Pauli Exclusion Principle (PEP)**
   - Violation of PEP by electrons
   - Theoretical model of small violations

Experimental aspects

2 **Experimental search for a possible PEP violation**

$'$Anomalous$'$ transitions

Experimental calculation of $\frac{\beta^2}{2}$

3 **Structure and characteristics of the detector**

High resolution detector

2 **Experimental search for a possible PEP violation**
- ′Anomalous′ transitions
- Experimental calculation of $\frac{\beta^2}{2}$

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

Part I

Theoretical aspects

The Pauli Exclusion Principle (PEP)

The Pauli Exclusion Principle (PEP) represents one of the fundamental principles of the modern physics 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

... also stressed yesterday by M. Berry

The Pauli Exclusion Principle (PEP)

.... 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.

R. Feynman, Feynman Lectures of Physics, 3rd Vol., Chap. 4, Addison-Wesley, Reading Massachusetts (1963).

... also stressed yesterday by A. Jabs and R. Hilborn

The Pauli Exclusion Principle (PEP)

A few papers on the PEP violation

- M. Goldhaber and G. Scharff-Goldhaber, 1948. Phys. Rev. 73, 1472-1473.
- H.S. Green, 1953. Phys. Rev. 90 (2), 270-273.
- P. A. M Dirac, The Principles of Quantum Mechanics (Clarendon Press, Oxford, 1958), Chapter IX
- W. Pauli, Die Allgemeihen Prinzipen der Wellenmechanik, in Handbuch der Physik (Springer-Verlag, Berlin, 1958), Bd. 5, T.1, Sect. 14
- E. Corinaldesi, Supplemento al Nuovo Cimento Serie I 5, 937943 (1967).
- E. Fischbach, T. Kirsten and O.Q. Shaeffer, 1968. Phys. Rev. Lett. 20 (18), 1012-1014.
- V. L. Luboshitz and M. I. Podgoretskii, Sov. Phys. JETP 33, 5 (1971)
- F. Reines and H.W. Sobel, 1974. Phys. Rev. Lett. 32 (17), 954
- R. D. Amado and H. Primakoff, Phys. Rev. C22, 1338 (1980)
- 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)
- L. B. Okun, Yad. Fiz. 47, 1192 (1988)
- A.B. Govorkov, 1989. Phys. Lett. A 137 (1-2), 7-10.

Violating theory for electrons

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

Ignatiev and Kuzmin model. The β parameter

3 states connected by creation - annihilation operators

- 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. The β parameter

The new creation - annihilation operators

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

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

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

Ignatiev and Kuzmin model. The β parameter

The new creation - annihilation operators

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 statistics.

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

Ignatiev and Kuzmin model. The β parameter

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

$$\begin{aligned} a^2 a^\dagger + \beta^2 a^\dagger a^2 &= \beta^2 a; \\ a^2 a^\dagger + \beta^4 a^\dagger a^2 &= \beta^2 a a^\dagger a; \\ a^3 &= \left(a^\dagger\right)^3 = 0 \end{aligned}$$

The particle number operator N in this model has the form:

$$N = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{pmatrix}$$

$$[N, a] = -a, \quad \left[N, a^\dagger\right] = a^\dagger$$

$$N = A_1 a^\dagger a + A_2 a a^\dagger + A_3$$

$$A_1 = \frac{-1 + 2\beta^2}{1 - \beta^2 + \beta^4}, \quad A_2 = \frac{-2 + \beta^2}{1 - \beta^2 + \beta^4}, \quad A_1 = \frac{2 - \beta^2}{1 - \beta^2 + \beta^4}$$

Ignatiev and Kuzmin model. The β parameter

- These new matrices describe **one level** which 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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Ignatiev and Kuzmin model. The β parameter

- ***"My conclusions concerning the possibility of constructions of a reasonable theory which violates the Pauli principle were pessimistic. The failure of attempts to violate (on paper) the Pauli principle is a consequence of rather general theorems based on fundamental properties of field theory"*.**

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

- ***"Thus it is impossible to construct a free field theory for small violations of Fermi or Bose statistics. We dont expect interactions to change this situation"*.**

O.W. Greenberg and R.N. Mohapatra, Preprint University of Maryland UM PP 89-030

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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"*.

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- *"The possibility that Bose and/or Fermi staitstics could be violated by small amount has been explored (...). As has been pointed in earlier work this is imposible (...). Nonetheless, even in absence of a quantum field theory of small violations of statistics, experimental tests of the validity of the exclusion principle and of Bose statistics would be of great interest, particularly because until recently the bounds on the validity of Fermi and Bose statistics were not of high precision"*.

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Quon theory of Greenberg

β **can be simply related to the** q **parameter of the quon theory of Greenberg**

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

quon algebra is a sort of weighted average between fermion and boson algebra:

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

or also

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

O.W. Greenberg, Phys. Rev. D, vol. 43, no. 12, (1991)

Part II

Experimental methods and VIP setup

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

VOLUME 59, NUMBER 22 PHYSICAL REVIEW LETTERS 30 NOVEMBER 1987

Local Quantum Field Theory of Possible Violation of the Pauli Principle

O. W. Greenberg and R. N. Mohapatra

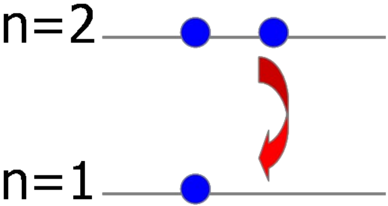
Center for Theoretical Physics, Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

(Received 5 August 1987)

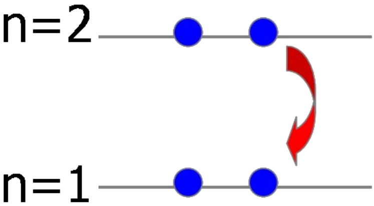
We generalize to a local relativistic quantum field theory a proposal of Ignatiev and Kuzmin for a single oscillator which has small violation of the Pauli principle and thus provide a theoretical framework which, for the first time, allows quantitative tests of the Pauli principle. Our theory provides 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.

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

Search for transitions which are prohibited by normal statistics



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



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

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

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

Multiconfiguration Dirac-Fock approach

Transition	Initial en.	Final en.	Transition	Radiative transition energy rate (s^{-1})	Multipole order
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.

Software for muonic atoms which take into consideration:

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

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

Energy of the anomalous transitions

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

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

"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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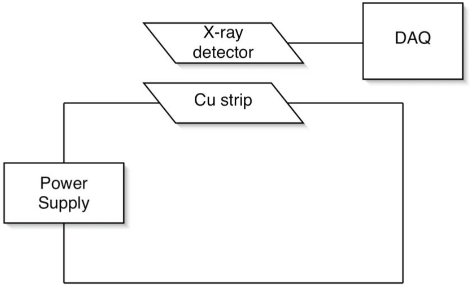
Ramberg and Snow experiment



- **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;**

$$N_{new} = \frac{1}{e}\int_T Idt$$

- **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**

$$GF \sim \frac{1}{\rho\sigma z}\frac{\pi}{8}$$

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

How to determine experimental limit on

The relation on the limit of violation probability

$$N_X \geq \frac{1}{2}\beta^2 N_{new}\frac{1}{10}N_{int} \times (geometricfactor)$$

$$= \frac{1}{2}\beta^2 \frac{1}{10}\frac{D}{\mu}\frac{\pi}{8}\frac{1}{z\sigma\rho}\int_T I(t)dt$$

Ramberg and Snow experiment

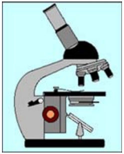
$$\int_T I(t)dt = 15.44 \cdot 10^6 C,\ D = 20 \cdot 10^{-3} m,\ \mu = 3.9 \cdot 10^{-8} m,$$
$$\rho = 8.96 \cdot 10^3 kg \cdot m^{-3},\ z = 1.5 \cdot 10^{-3} m,$$

$$N_X \geq \beta^2 \left(0.9 \cdot 10^{28}\right) \quad \Longrightarrow \quad \frac{\beta^2}{2} \leq 1.7 \cdot 10^{-26}\ (95\% C.L.)$$

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

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...

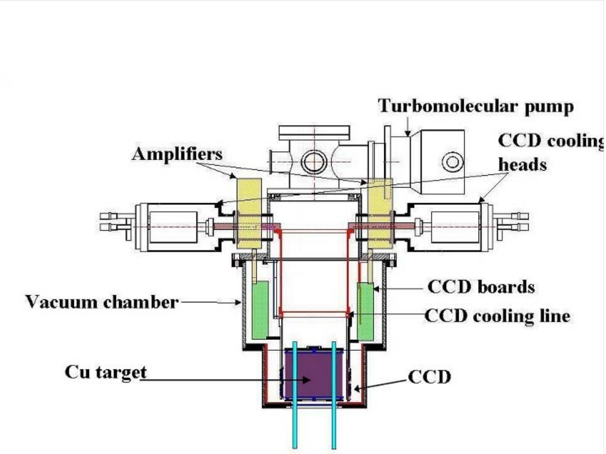
$$\frac{1}{2}\beta^2 \leq 1.7 \times 10^{-26}$$

Ramberg Snow Phys. Lett. B238 (1990) 438

...to

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

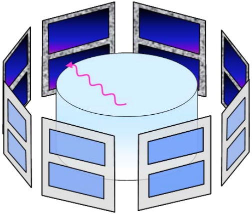
The VIP setup equipped with 16 CCDs (general layout)

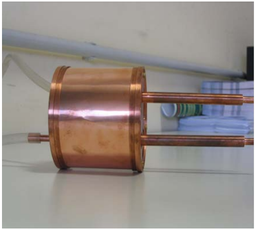


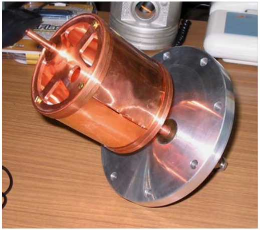
The VIP setup equipped with 16 CCDs
Cu target

VIP Cu target cylinder:

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



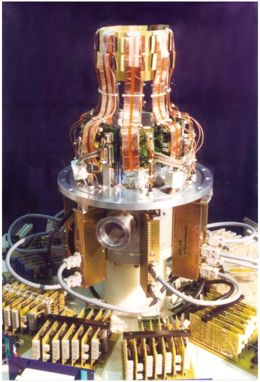




The CCD detectors are at a distance of 2.3 cm from Cu cylinder.

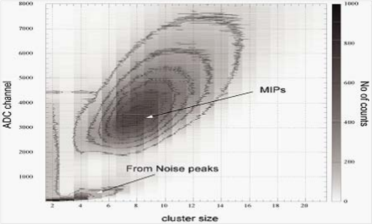
The VIP setup equipped with 16 CCDs
CCD Detector

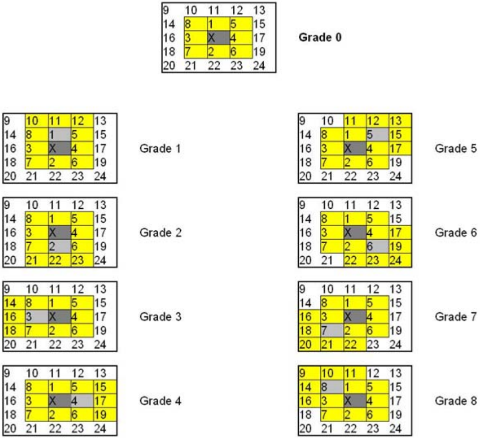
- **16 CCD-55 Charged Coupled Devices chips Marconi Applied Technologies, CCD55-30;**
- **are designed for low temperature operation** ($\backsim 150K$)**, to minimize the thermal noise ;**
- **1242rows x 1152columns=1430784** *pixels*
  a pixel size of 22.5x22.5 *mm*
  an effective area of 7.3 cm^2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

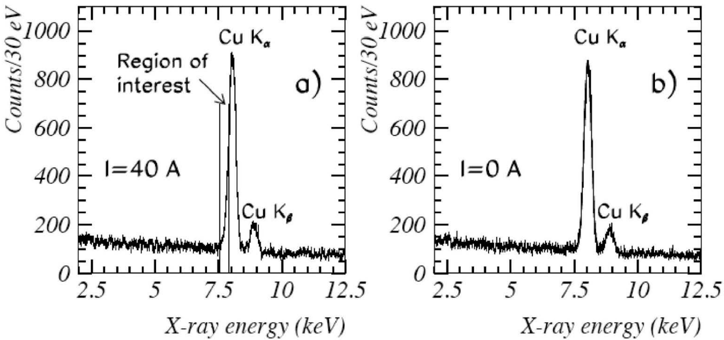
Experimental results

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;
- April 2006: installation of the final shielding for the VIP setup and start DAQ for 2 years measurements, with and without current.

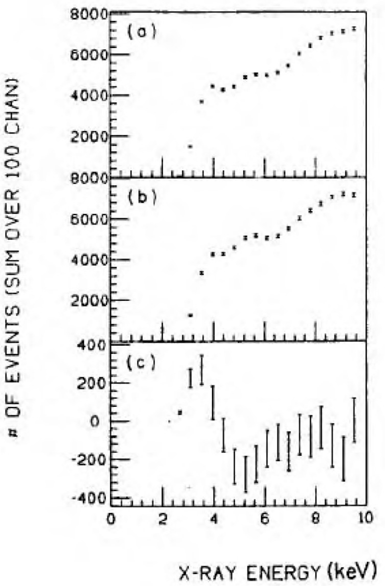
VIP setup in LNF laboratory

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).

Energy spectra - RS experiment



No Cu peaks because of the anticoincidence scintilators.

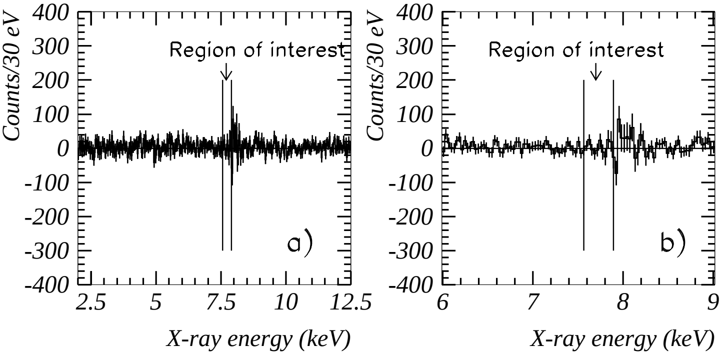
The ′region of interest′

- 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.**

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 **:**

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

Phys. Lett. B 641, 18 (2006)

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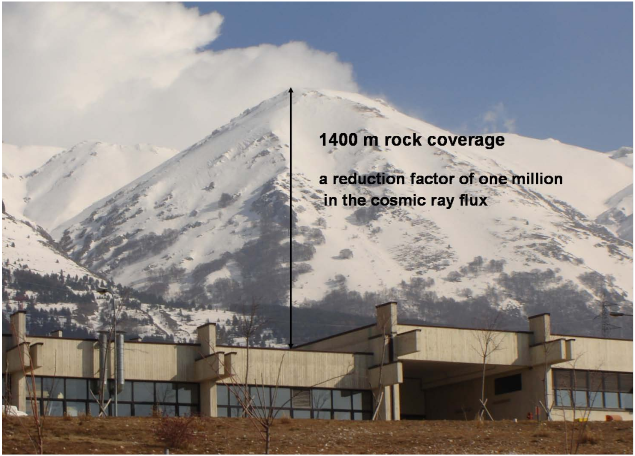
Gran Sasso underground laboratory



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

VIP in Gran Sasso underground laboratory

VIP in Gran Sasso underground laboratory

VIP in Gran Sasso underground laboratory

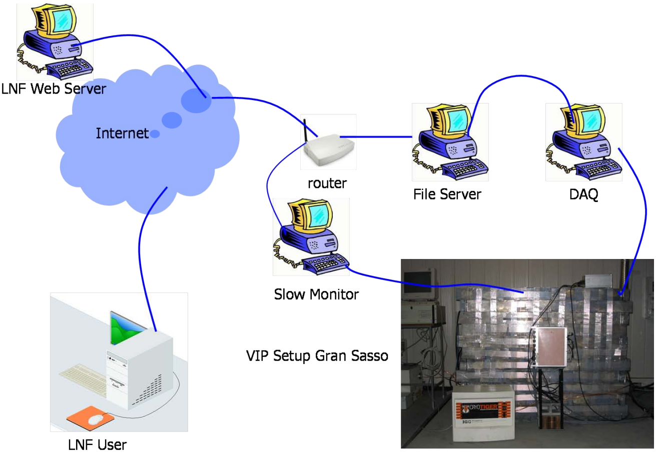
Preliminary LNGS results (January 2008) - L. Sperandio Ph. D. Thesis

- **236005 minutes of measurements with a 40 A current circulating in the copper target;**
- **172685 minutes of measurements without circulating current,**

The new limit

$$\frac{\beta^2}{2} \leq 5.7 \times 10^{-29} at\ 99.8\%\ CL.$$

VIP in Gran Sasso underground laboratory



Conclusions and Perspectives

A new limit for the PEP violation for electrons was established: 4.5×10^{-28}. After one year of data taking the LNGS preliminary limit for the PEP violation for electrons was lowered to 6.0×10^{-29}, about three orders of magnitude better than the RS experiment.

The VIP measurement will contiune until the end of 2008 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.

2008: Feasibility test for VIP2
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Thank you!

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