The VIP experiment: New experimental limit on the Pauli exclusion principle violation by electrons

VIP: VIolation of the Pauli Exclusion Principle

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on behlaf of VIP Collaboration

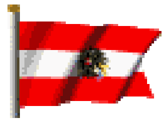
XI Frascati Spring School "BRUNO TOUSCHEK"
LNF, May 14th– 18th, 2007, Frascati, Italy

VIP Collaboration

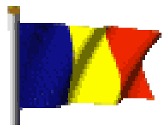
LNF- INFN, Frascati, Italy

INFN, Trieste, Italy

SMI, Vienna, Austria



IFIN – HH, Bucharest, Romania



The Pauli Exclusion Principle (PEP)

The Pauli Exclusion Principle (PEP) represents one of the fundamental principles of the modern physics and all our comprehension of the surrounding matter is based on it.

Even if today there are no compelling reasons to doubt its validity, it still spurs a lively debate on its limits, as testified by the abundant contributions found in literature, especially for those theories related to possible PEP violation coming from new physics.

→ **it seems appropriate to carry out precise test of the PEP validity**

Significant papers on the PEP violation

E. Fermi, Atti. Sci. It. Prog. Sci. 22 Riunione (Bari 1933), vol. 3, p.7; E. Fermi, Scientia 55, 21 (1934)

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

V. L. Luboshitz and M. I. Podgoretskii, Sov. Phys. JETP 33, 5 (1971)

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)

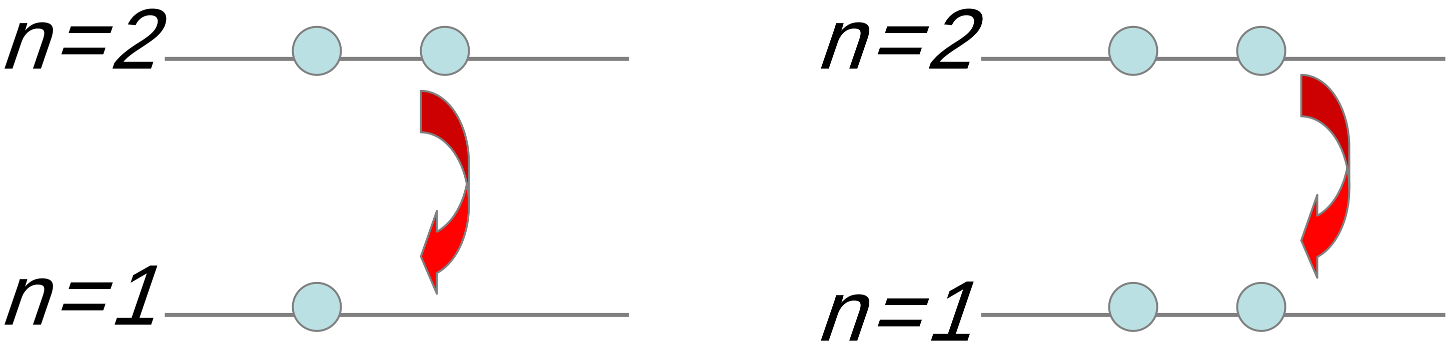
L. B. Okun, Yad. Fiz. 47, 1192 (1988)

Goal of VIP

The VIP experiment has the scientific goal to perform an experimental check of the Pauli Exclusion Principle for electrons to and to ***improve the actual limit of the PEP for electrons*** *(which is around 10^{-26}),* ***by 4 orders of magnitude****, arriving to the probability of violation of PEP by electrons of* **(10^{-29}-10^{-30})**

Experimental method

Search for anomalous X-ray transitions



Normal 2p →1s transition

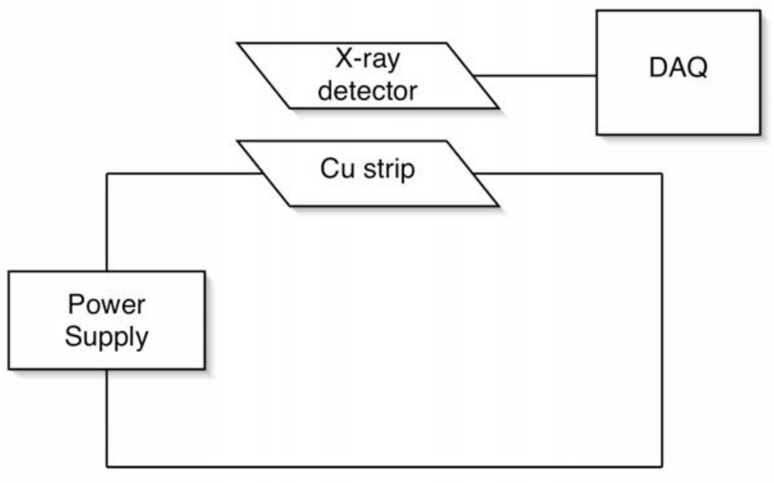
2p →1s transition violating Pauli principle

8.04 keV in Cu	**~ 7.7 keV in Cu**

The present experiment limit: Ramberg and Snow (RS) experiment

(Phys. Lett. B238 (1990) 438)

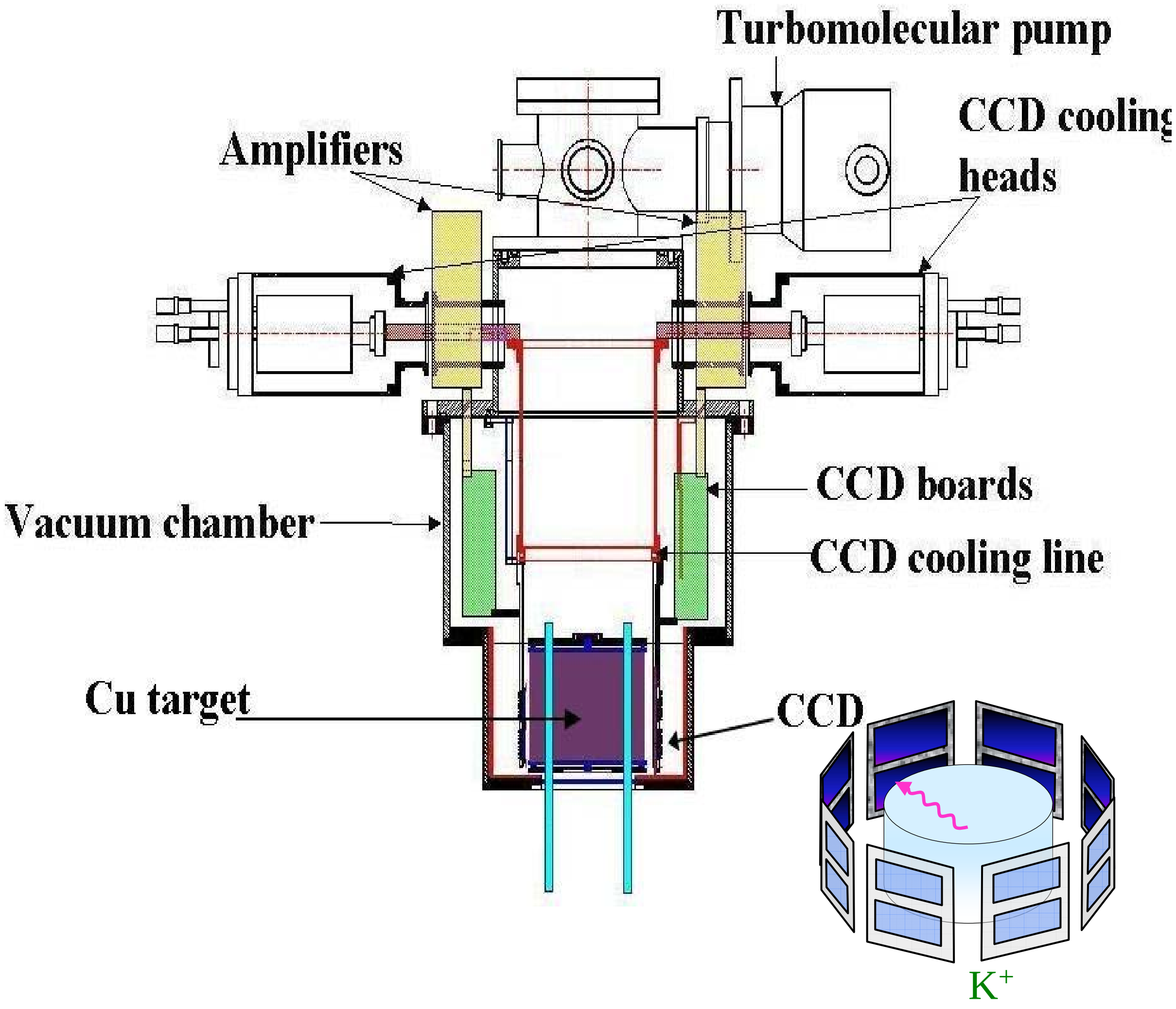
The ideea – to introduce new electrons into a Cu strip, by circulating current and to search for anomalous electronic transitions in Cu <u>(~ 7.6 keV instead of 8.04 keV)</u> if one of the new electrons is capturated by the Cu atom and cascades down to the 1s states already filled by 2 electrons of opposite spin.



Actual experimental limit for the probability of the violation of the Pauli Exclusion Principle for electrons (R&S):

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

The VIP setup equipped with 16 CCDs (higher sensitive apparatus)



Why at Gran Sasso?

The 4 orders of magnitude to be gained in the value of the PEP for electrons should arrive from geometrical and detector reason (using high resolution CCD)

and

an assumed background reduction ~ factor 100 (Gran Sasso)

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

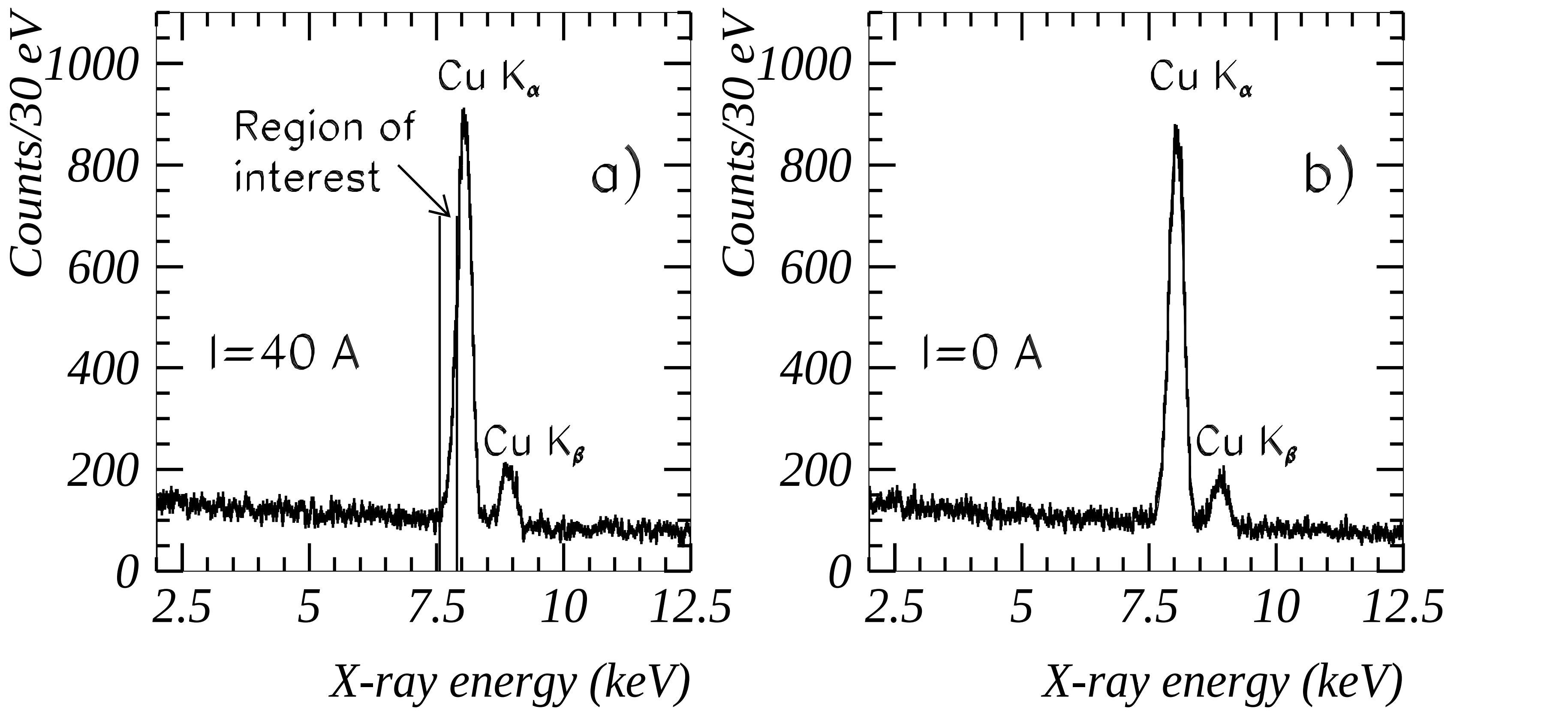
Experimental activities since October 2004

- *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.*

Measurements at LNF with VIP setup

VIP setup in laboratory

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

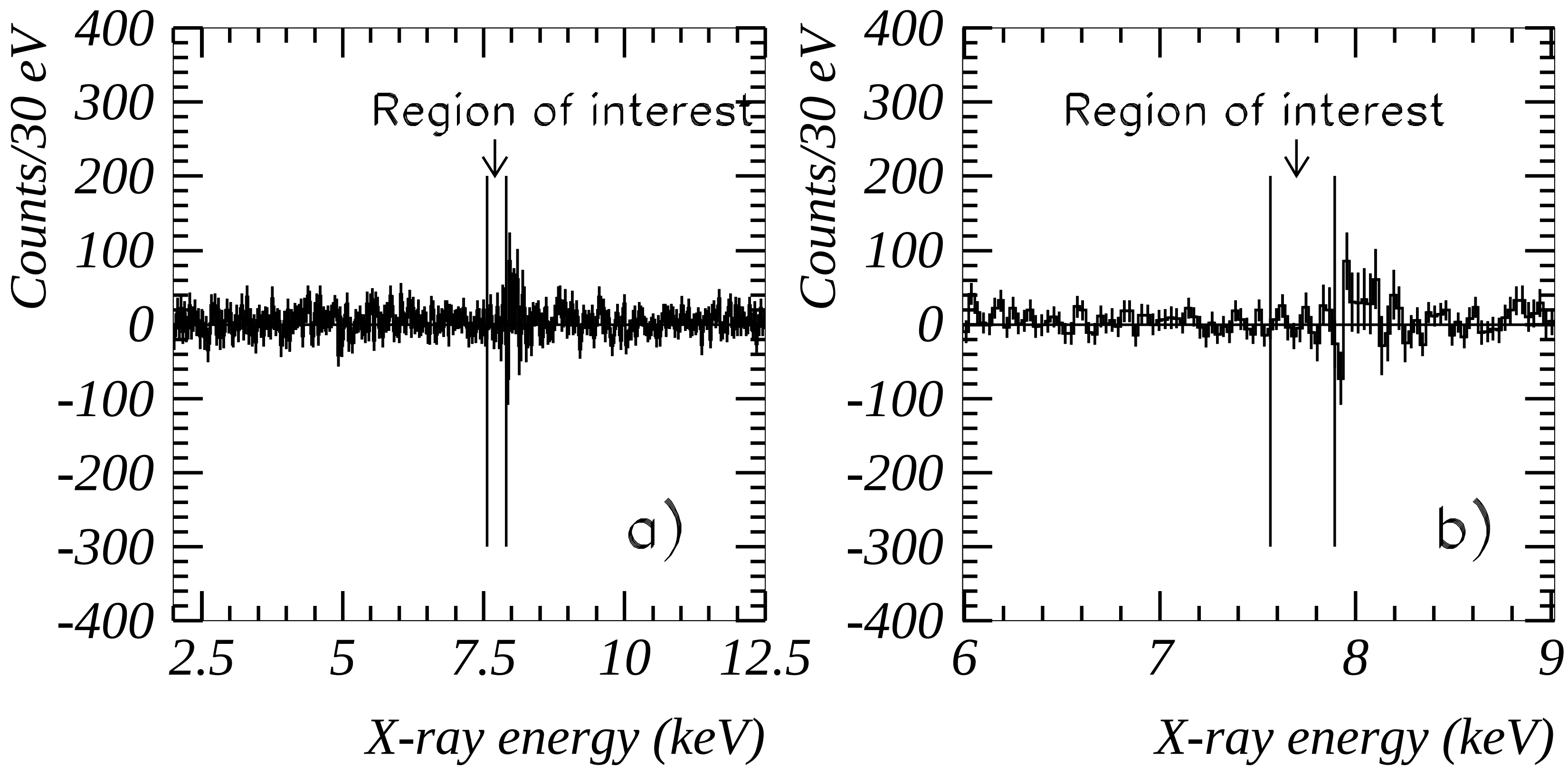


14510 minutes (about 10 days) of measurements for each type of measurement (with and without circulating current)

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 region of interest where an eventual PEP violating evidence might occur is ±170 eV around the position of the anomalous transition (7.729 keV).



Determination of the PEP violation probability limit (II)

$$\Delta N_X \geq \frac{\beta^2}{2} \times f(I, \Delta t, geometric \; f \ldots$$

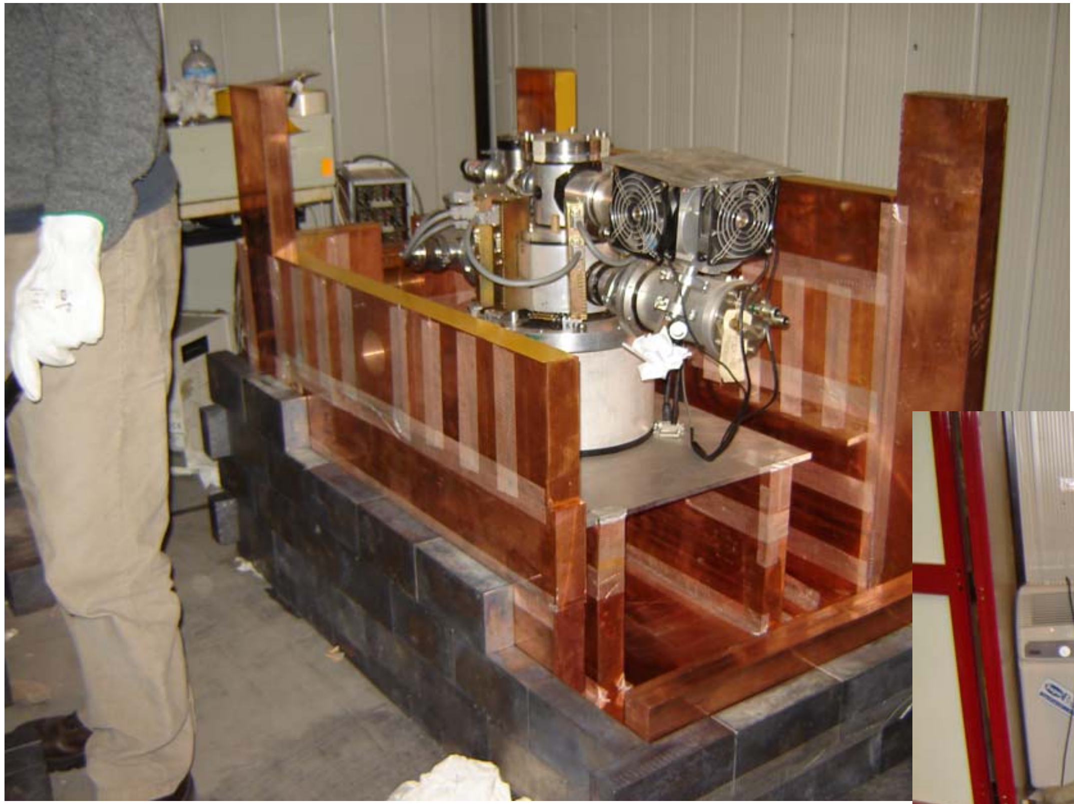
Phys. Lett. B 641, 18 (2006)

$$\frac{\beta^2}{2} \geq 4.5 \times 10^{-28}$$

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

VIP setup @ Gran Sasso-INFN underground laboratory

VIP setup at Gran Sasso



VIP setup at Gran Sasso

Non official results

Today we have got about 1 year of data taken at LNGS with total shielding.

Performing the calculations in an analogous way we have found for the violating parameter the value:

$$\beta^2/2 \leq 6.5\times 10^{-29}$$

We have thus improved the limit obtained by Ramberg & Snow by a factor ~ 250.

(about 3 orders of magnitude better)

RESULT NOT YET PUBLISHED

The VIP measurement will continue 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^{-29}- 10^{-30} region, which is of particular interest, for all those theories related to the possible PEP violation coming from new physics.

Interest in experimental test of the Pauli principle for electrons:

The are several theoretical reason to push the experimental limit in the region of 10^{-30}: for example the validity of Pauli principle in a higher-dimensional spacetime with small violation in the 3 +1 known dimension; or strings and superstrings etc.

"More recently … membrane theorists have been speculating on a large compactification radius for one of their eleven dimensions, which could give a ratio (for PEP violation) of 10^{-30}" [1]

[1] I. Duck and E. C. G. Sudarshan: Towards an understanding of the spin-statistics theorem, Am. J. Phys, 66 (1998) 284.

SPARES

Determination of the PEP violation probability limit

The number of "new" electrons passing through the Cu conductor:	$N_{new} = \frac{1}{e}\int_T I(t)dt$
The minimum number of scattering process on the atoms of the copper lattice, per electron: *(D=Length of the copper electrode* *μ = mean free path of electron in copper)*	$N_{int} = diam/m.f.p. = D/\mu$
We assume that the capture probability is> 1/10 of the scattering probability	> (1/10) 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:	$\lambda = 1/\sigma\rho$
If z is the copper thickness, the fraction of visible current to the detector will be	λ/z
Expected number of X-rays:	$N_X \geq \frac{1}{2}\beta^2 N_{new}\frac{N_{int}}{10} = \frac{\beta^2(\Sigma I\Delta t)D}{e\mu\rho z\sigma}$

Determination of the PEP violation probability limit (II)

$$\Delta N_X \geq \frac{1}{2}\beta^2 N_{new}\frac{N_{int}}{10}\times(g.f)=\frac{\beta^2}{2}\frac{(\sum I\Delta t)D}{e\mu}\frac{1}{10}\times(g.f)$$

$\sum I\Delta t = 34.824\cdot 10^6 C;\quad D = 8.8cm;\quad \mu = 3.9\cdot 10^{-8} m;\quad e = 1.602\cdot 10^{-19} C$

$\Delta N_X = -21 \pm 73 \;/\; g.f = 1\%$

@ I=40A → Nx= 2721 ± 52

@ I=0A → Nx= 2742 ± 52

$$\frac{\beta^2}{2} \leq 4.5 \times 10^{-28}$$

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

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:

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

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

$D = 0.025m$

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

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

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

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

$e = 1.6 \cdot 10^{-19} C$

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

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

Dirac-Fock multiconfiguration method

Software for muonic atoms

↓

non-antisymmetrized e^- !!!

It takes into consideration:	- *relativistic corrections*
	- *lamb-shift*
	- *Breit operator*
	- *radiative corrections*

***Self-consistent method* for the optimization of the parameters**

Transition energies of the anomalous X-rays in Copper

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

Multiconfiguration Dirac-Fock approach

core: (1s)2(2s)2(3s)2(2p*)2(3p*)2(2p)4(3p)4(3d*)4(3d)

Transition	Initial en.	Final en.	Transition energy	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	K_α
$3p_{1/2}$ - $1s_{1/2}$	-44998	-53528	8530	2.78E+13	E1	K_β
$3p_{3/2}$ - $1s_{1/2}$	-44996	-53528	8532	2.68E+13	E1+M2	K_β

- Normal copper: ~ 8040 eV (2p → 1s)
- Note: similar value obtained by S. Di Matteo e L. Sperandio in the "sudden approximation".

Tests of PEP for nucleons

Search for non-paulian transitions in ^{23}Na and ^{127}I

R. Bernabei [a], P. Belli [a], F. Montecchia [a], M. De Sanctis [b], W. Di Nicolantonio [b], A. Incicchitti [b], D. Prosperi [b], C. Bacci [c], C.J. Dai [d], L.K. Ding [d], H.H. Kuang [d], J.M. Ma [d]

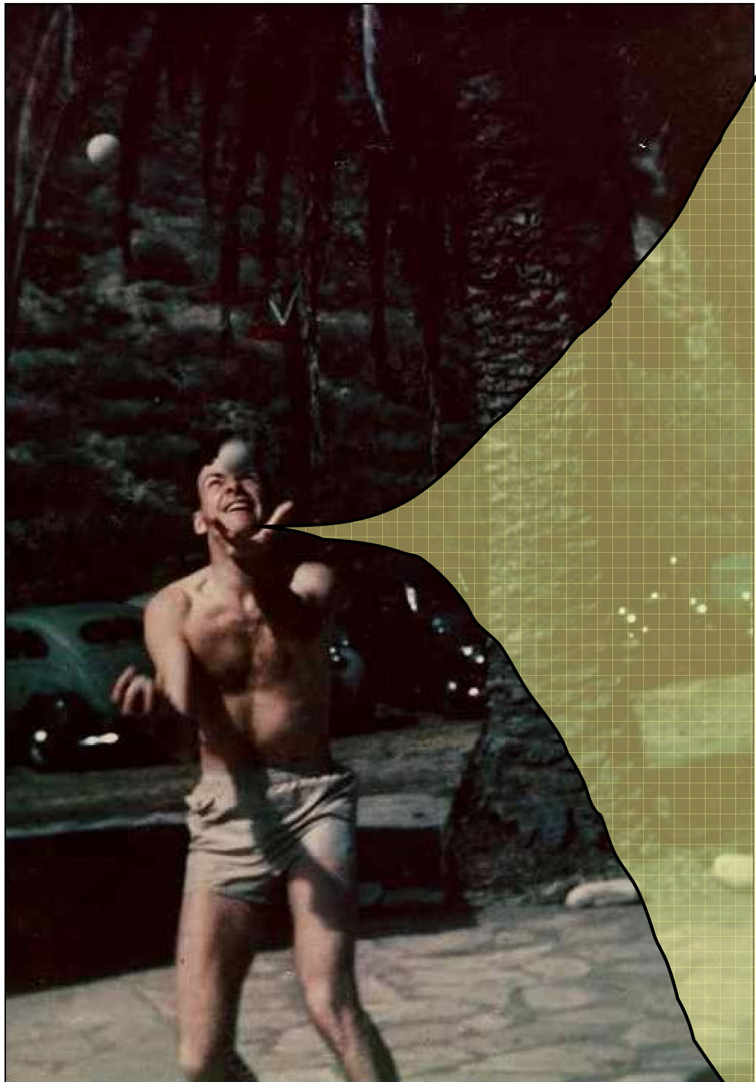
[a] *Dip. di Fisica, Universita' di Roma "Tor Vergata" and INFN, sez. Roma2, I-00133 Rome, Italy*
[b] *Dip. di Fisica, Universita' di Roma "La Sapienza" and INFN, sez. Roma, I-00185 Rome, Italy*
[c] *Dip. di Fisica, Universita' di Roma III and INFN, sez. Roma, I-00185 Rome, Italy*
[d] *IHEP, Chinese Academy, P.O. Box 918/3, Beijing 100039, China*

Physics Letters B 408 (1997) 439–444

NEW EXPERIMENTAL LIMITS ON VIOLATIONS OF THE PAULI EXCLUSION PRINCIPLE OBTAINED WITH THE BOREXINO COUNTING TEST FACILITY.

By Borexino Collaboration (H.O. Back *et al.*). Jun 2004. 10pp.
Submitted to Eur.Phys.J.C ;
e-Print Archive: **hep-ph/0406252**

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, 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

Transition energies the anomalous X-rays in Copper:

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

Multiconfiguration Dirac-Fock approach, 26 March 2005

Transition	Initial en.	Final en.	Transition energy	Radiative trans. rate (s-1)	Multipole order
core: (1s)2(2s)2(3s)2(2p*)2(3p*)2(2p)4(3p)4(3d*)4(3d)					
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
2p1/2-2s1/2	-44998	-45934	936	1.64E+12	E1
2p3/2-2s1/2	-44996	-45934	938	1.49E+12	E1+M2

- **Normal copper: ~ 8040 eV 2p – 1s**
- Note: similar value obtained by Sergio di Matteo in the "sudden approximation"

VIP Slow Controls and Monitoring