VIP-2 status

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Centro Fermi, LNF (INFN)

On behalf of VIP Collaboration

LNGS Scientific committee

1-2 April 2019

Content:

Brief reminder and update of the VIP-2 scientific case

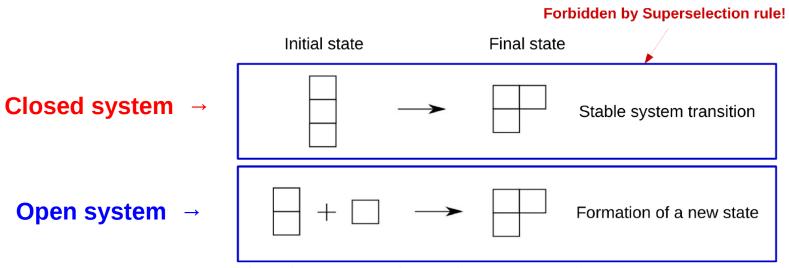*VIP-2 **tests the Pauli Exclusion Principle** (PEP) (spin-statistics) **for electrons** in a clean environment (LNGS) using a method which respects the Messiah-Greenberg superselection rule.*
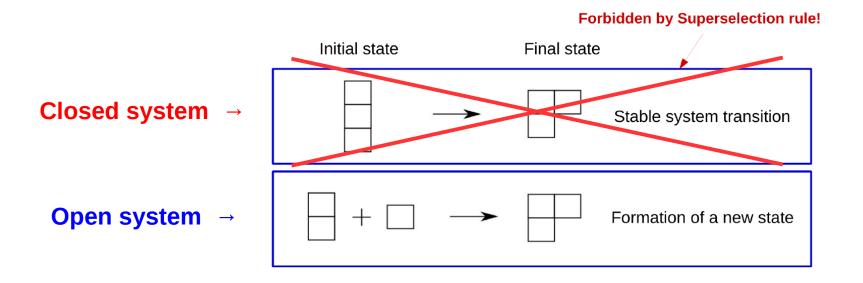
Messiah – Greenberg superselection rule

Superpositions of states with different symmetry are not allowed → transition probability between two symmetry states is ZERO

Forbidden by Superselection rule!

Initial state   Final state

Closed system →

Stable system transition

Open system →

Formation of a new state

A. M. L. Messiah and O. W. Greenberg, Phys. Rev. 136 (1964) B248.

O. W. Greenberg and A. M. L. Messiah, Phys. Rev. 138 (1965) B1155.

G. Gentile, NuovoCimento 17, 493(1940)

H. S. Green, Phys. Rev. 90 (1953) 270.

A. Y. Ignatiev and V. A. Kuzmin, JETP Lett. 47 (1988) 4.

V. N. Gavrin, A. Y. Ignatiev and V. A. Kuzmin, Phys. Lett. B 206 (1988) 343.

O.W. Greenberg, Phys. Rev. Lett. 64, 705 (1990)

R.N. Mohapatra, Phys. Lett. B 242, 407 (1990)

O.W.Greenberg, R.C.Hilborn, Fund.Phys.29, 397(1999)

Messiah – Greenberg superselection rule

Superpositions of states with different symmetry are not allowed → transition probability between two symmetry states is ZERO

Closed system →

Open system →

Forbidden by Superselection rule!

Initial state   Final state

Stable system transition

Formation of a new state

VIP sets the best limit on PEP violation for an elementary particle respecting the M-G superselection rule

Experimental method

Search for anomalous X-ray transitions performed by electrons introduced in a target _trough a DC current (open system)_

$n=2$ ———○——○——— $n=2$ ———○——○———

$n=1$ ———○——— $n=1$ ———○——○———

Normal 2p → 1s transition   2p → 1s transition violating Pauli principle

~ 8.05 keV in Cu   ~ 7.7 keV in Cu

standard QED calculations accounting for different inner electronic clouds shieldings

Paul Indelicato (Ecole Normale Supérieure et Université Pierre et Marie Curie)
Multiconfiguration Dirac-Fock approach

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)** <u>noncommutative spacetime</u>. *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."

Update of the scientific case:

2 classes of PEP violation models, induced by:

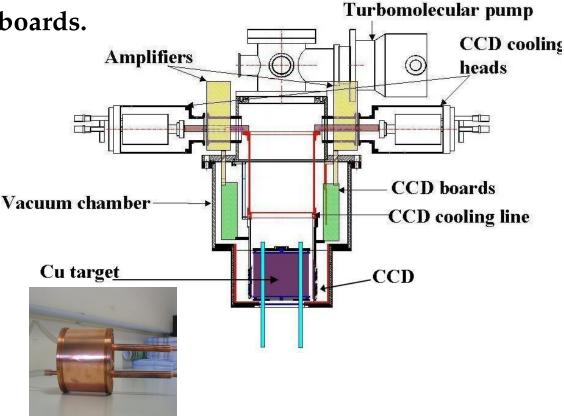*- Particle properties -> VIP-2 with current circulating inside a target (*open system*)*

*- Space-time properties (*closed systems*) – i.e. non-commutative geometries: VIP-Lead and related*
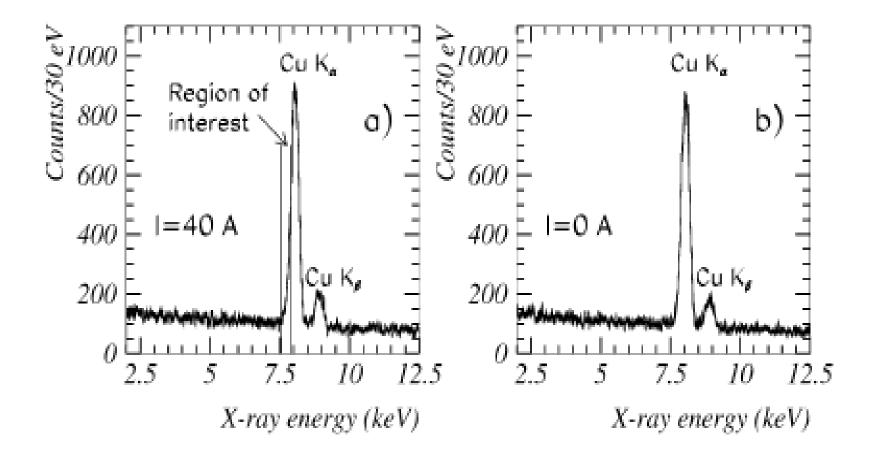
a) copper ultrapure cylindrical foil
b) surrounded by 16 Charge Coupled Devices (CCD)
   res. at 8 keV 320 eV (FWHM)
c) inside a vacuum chamber: CCDs cooled to 168K by a
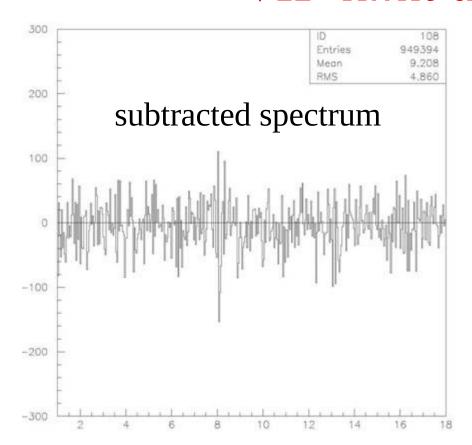   cryogenic system
d) amplifiers + read out ADC boards.

Turbomolecular pump
CCD cooling heads
Amplifiers
Vacuum chamber
CCD boards
CCD cooling line
Cu target
CCD

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

At 8 keV energy resolution of 320 eV (FWHM)

VIP limit at LNGS

ID	108
Entries	949394
Mean	9.208
RMS	4.860

subtracted spectrum

PEP violation
Probability:

(L. Sperandio Ph D thesis)

$$\beta^2/2 \le 4.7 \times 10^{-29}$$

We have thus improved the limit obtained by Ramberg & Snow by a factor ~ 400

(Foundation of Physics 41 (2011) 282+ other papers)

From VIP to VIP-2 , the goal ..

From:

$$\beta^2/2 \leq 4.7 \times 10^{-29}$$

to

$$\beta^2/2 \leq (5) x 10^{-31}$$

a) Silicon Drift Detectors (SDDs)   → higher resolution, faster (triggerable) detectors

X-ray tube

Veto scintillators

copper strips

copper conductor

SDDs

10 cm

Fig. 1 The side views of the design of the core components of the VIP-2 setup, including the SDDs as the X-ray detector, the scintillators as active shielding with silicon photomultiplier readout

4 arrays of 2 x 4 SDDs
8mm x 8mm each

SDD Anode

Ring 1

34 mm

18 mm
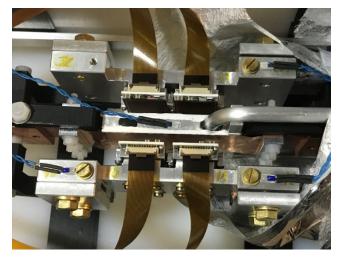
8 mm

8 mm

liquid argon closed
circuit cooling
- 170 °C

VIP-2 major upgrade

b) **2 strip shaped Cu targets** (25 μm x 7 cm x 2 cm) **more compact target → higher acceptance, thiner → higher efficiency**

DC current supply to Cu bars

X-ray tube

Veto scintillators
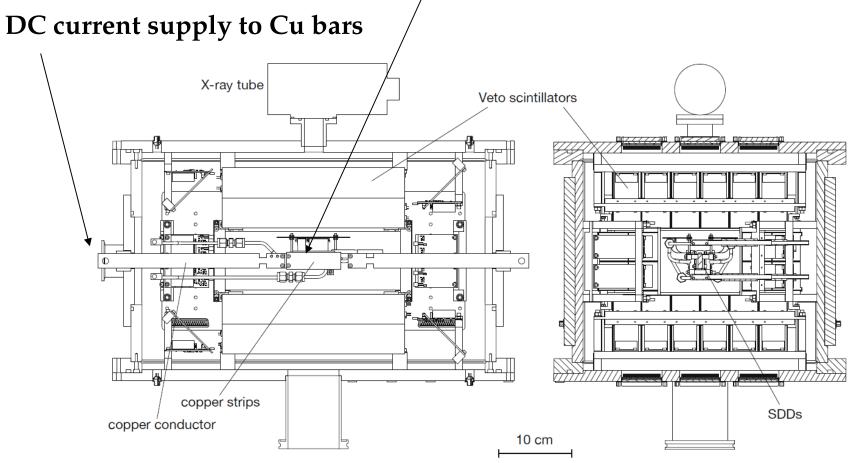
copper strips
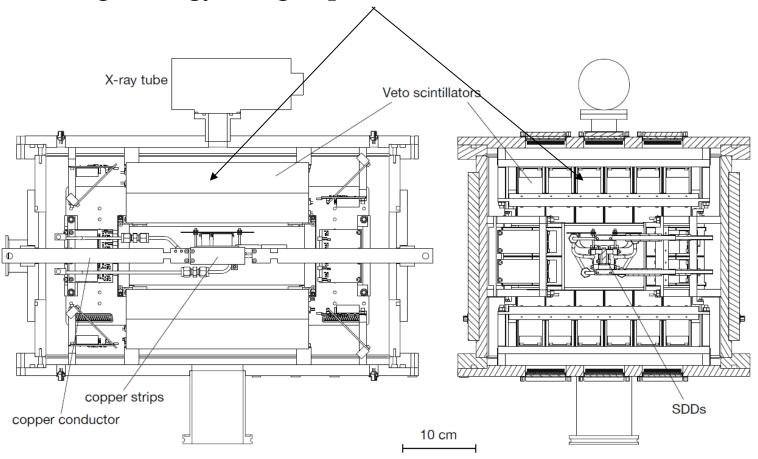
copper conductor

SDDs

10 cm

Fig. 1 The side views of the design of the core components of the VIP-2 setup, including the SDDs as the X-ray detector, the scintillators as active shielding with silicon photomultiplier readout

VIP-2 major upgrade

c) VETO system (32 plastic scintillators + SiPMs read out) → rejection of background (high energy charged particles) from outside the detector

Fig. 1 The side views of the design of the core components of the VIP-2 setup, including the SDDs as the X-ray detector, the scintillators as active shielding with silicon photomultiplier readout

Status of the VIP-2 experiment

VIP-2 setup and data taking:

1) VIP-2 with 6 SDD (SIDDHARTA type) installed at LNGS in end 2015 – data taking (no shielding) till end of 2017

2) VIP-2 with final SDDs (4 arrays of 2x4 SDD detectors) installed at LNGS in April 2018; test and data taking without shielding till November 2018

3) Shielding installed in November 2018 – data taking ongoing

4) Optimization of the veto system ongoing

VIP-2 with the final 4 SDD arrays

Was installed at LNGS in April 2018:

Shielding installation in November 2018:

VIP-2 with final 4 SDD arrays

Shielding installation in November 2018:

VIP-2 preliminary results
and refinement of the data analyses

According to the requirements of the VIP-2 referees improved Bayesian data analysis procedure was implemented (inspired to A. Caldwell, K. Kröninger, Phys. Rev. D 74, 092003 (2006))

$$p(S, B|\text{data}) = \frac{p(\text{data}|S, B) \cdot p_0(S) \cdot p_0(B)}{\int p(\text{data}|S, B) \cdot p_0(S) \cdot p_0(B) dS dB}.$$

Joint *p.d.f.* from the Bayes theorem. Number of events in each bin fluctuate around the mean according to a Pois. Dist.
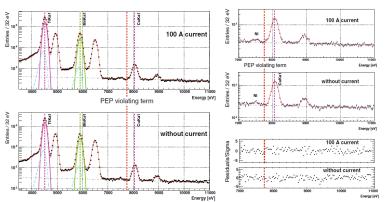
Posterior *p.d.f.* (model needs in input the bkg. and sig. normalised shapes):
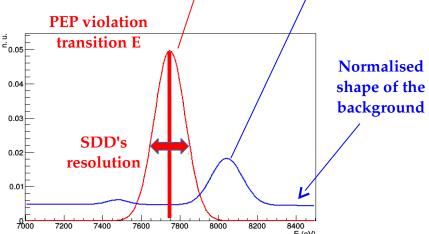
$$P(S|\text{data}) = \int P(S, B|\text{data}) \, dB$$

Likelihood →
$$P(\text{data}|S, B) = \prod_{i=1}^{N} \frac{\lambda_i(S, B)^{n_i} \cdot e^{-\lambda_i(S,B)}}{n_i!}$$

$$\lambda_i = \lambda_i(S, B) = S \cdot \int_{\Delta E_i} f_S(E) dE + B \cdot \int_{\Delta E_i} f_B(E) dE,$$

Taking advantage of our last analysis the input normalised shape of the bkg spectrum is obtained from a symultaneous fit:

PEP violation transition E

SDD's resolution

Normalised shape of the background

Eur. Phys. J. C (2018) 78:319

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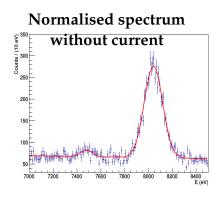**Posterior *p.d.f.* (model needs in input the bkg. and sig. normalised shapes):**
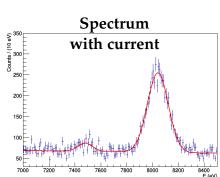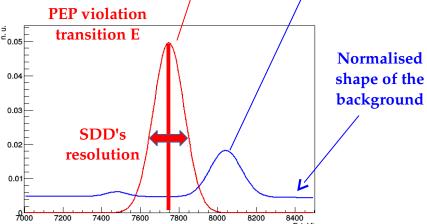
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Normalised spectrum without current

Spectrum with current

PEP violation transition E

SDD's resolution

Normalised shape of the background

Dec. 2018 – Feb. 2019 Data analysis

The prior probability for the number of expected signal events is assumed flat up to a maximum S_{max} consistent with existing limits [Eur. Phys. J. C (2018) 78:319].
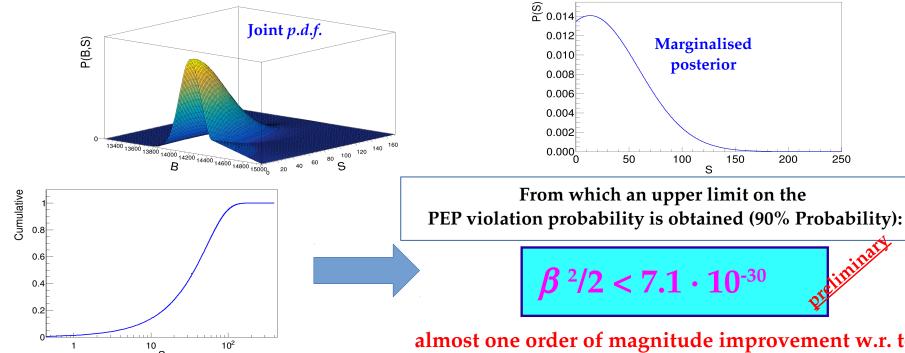
$$p_0(S) = \begin{cases} \frac{1}{S_{max}} & 0 \leq S \leq S_{max} \\ 0 & \text{otherwise} \end{cases}$$

The mean value for the expected number of bkg. Events μ_b mediated from the measured bkg. Spectrum. Prior is assumed Gaussian with a width $\sigma_b = \mu_b/2$.

$$p_0(B) = \begin{cases} \frac{e^{-((B-\mu_B)^2/2\sigma_B^2)}}{\int_0^\infty e^{-((B-\mu_B)^2/2\sigma_B^2)} dB} & B \geq 0 \\ 0 & B < 0 \end{cases}$$

The posterior is calculated by means of Markow chain Monte Carlo techniques

Joint *p.d.f.*

Marginalised posterior

From which an upper limit on the
PEP violation probability is obtained (90% Probability):

$$\beta^2/2 < 7.1 \cdot 10^{-30}$$

preliminary

almost one order of magnitude improvement w.r. to VIP

Data analyses

Article
On the Importance of Electron Diffusion in a Bulk-Matter Test of the Pauli Exclusion Principle

Edoardo Milotti [1,*] , Sergio Bartalucci [2], Sergio Bertolucci [3], Massimiliano Bazzi [2],
Mario Bragadireanu [2,4], Michael Cargnelli [2,5], Alberto Clozza [2], Catalina Curceanu [2,4,6],
Luca De Paolis [2], Jean-Pierre Egger [7], Carlo Guaraldo [2], Mihail Iliescu [2],
Matthias Laubenstein [8] , Johann Marton [2,5], Marco Miliucci [2], Andreas Pichler [2,5],
Dorel Pietreanu [2,4], Kristian Piscicchia [2,6], Alessandro Scordo [2], Hexi Shi [9],
Diana Laura Sirghi [2,4], Florin Sirghi [2,4], Laura Sperandio [2], Oton Vázquez Doce [2,10],
Eberhard Widmann [5] and Johann Zmeskal [2,5]

- In [E. Ranberg, G. A. Snow, Phys. Lett. B (1990) 238, 438] the scattering frequency in a **straight path** of the Electron across the target is considered.

- In [Entropy 2018, 20(7), 515; https://doi.org/10.3390/e20070515] the **random walks** of the electrons when crossing the target is described in terms of a diffusion transport model. This needs further investigation and generalization to a quantistic framework.

SUMMARIZING:

Full statistics analysed (A. Pichler PHD thesys) $\beta^2/2 < 1.6 \cdot 10^{-29}$ Paper under finalization $\longrightarrow$

	$\frac{\beta^2}{2}$	Reference
VIP limit	$\leq 4.7 \cdot 10^{-29}$	Foundation of Physics 41 (2011) 282
Pre-VIP2 with SIDDHARTA SDDs and without shielding	$\leq 3.4 \cdot 10^{-29}$	Eur. Phys. J. C, (2018) 78:319
VIP2 new SDDs with shielding	$\leq 7.1 \cdot 10^{-30}$	Very preliminary
Considering random walks of the electrons	$\leq 4.4 \cdot 10^{-41}$	Very preliminary

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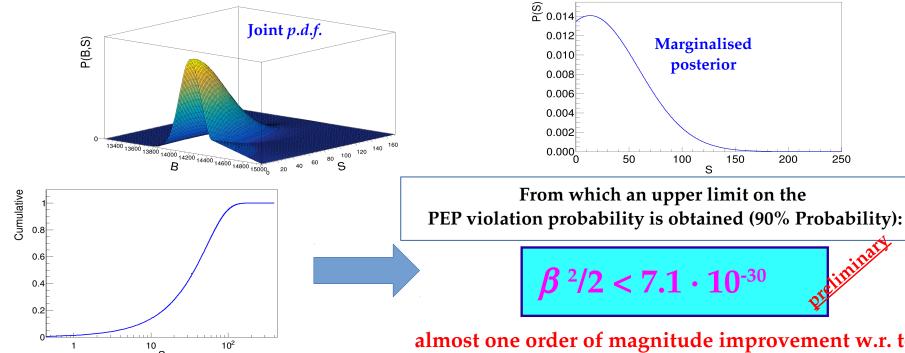
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preliminary

almost one order of magnitude improvement w.r. to VIP

PEP violation in quantum gravity

Quantum gravity models can embed **PEP violation transitions!**

Prototipe example is θ-Poincarè non-commutative space-time.

θ-Poincarè is explicitely unitary at tree level but S-matrix does not commute with CPT.

Moreover non-commutative space time implies non-locality and a-causality at the microscopic non-commutativity scale.

The spin statistics theorem was conceived assuming:

causality, locality, Lorentz invariance ..

$$\downarrow$$

θ-Poincarè can elude the Pauli theorem

PEP violation in quantum gravity

A. Addazi, A. Marianò, Fudan University

VIP-2 underground experiment as a *Crash-Test* of Non-Commutative Quantum Gravity

Pauli Exclusion Principle (PEP) violations induced from non-commutative space-time can be searched VIP-2 experiment set-up. We show that the limit from VIP-2 experiments on non-commutative space-time scale Λ, related to energy dependent PEP violations, are severe: κ-Poincaré non-commutativity is ruled-out up to the Planck scale. In the next future θ-Poincaré will be probed until the Grand-Unification scale! This highly motivates Pauli Exclusion Principle tests from underground experiments as a test of quantum gravity and space-time microscopic structure.

PEP violation in quantum gravity

Differences of θ-Poincarè w. r. to effective models:

- does not respect the M-G superselection rule (transition amplitude from a state of two different fermions to a state of two identical fermions is not zero) →

can be tested with closed systems (ex. using Fermi see electrons in the conductor as test electrons, <u>no current</u>);

- the violation probability depends on the PEP violating process transition energy (suppressed with the non-commutativity energy scale) →

it is important to test different atomic species → different Z → different ΔE for the measured transition;
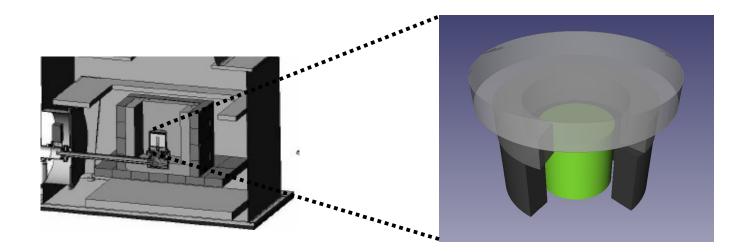
Preliminary test was already performed for $_{82}$Pb, we plan to repeat with other elements ($_{73}$Ta, $_{23}$V ...)
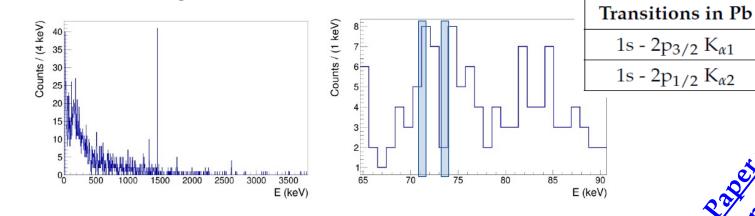
VIP-Lead

High purity Ge detector measurement (Matthias Laubenstein):

- Ge detector surrounded by roman lead target + complex electrolytic Cu + Pb shielding

- 10B-polyethylene plates reduce the neutron flux towards the detector

- shield + cryostat enclosed in air tight steel housing flushed with nitrogen to avoid contact with external air (and thus radon).

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Extremely low statistics in the two ROI regions compatible with the mean bkg: b = 4.4 counts/keV

Transitions in Pb	forb.	allow.
1s - 2p$_{3/2}$ K$_{\alpha1}$	73713	74961
1s - 2p$_{1/2}$ K$_{\alpha2}$	71652	72798

Paper under finalization

Figure 1. Total measured X-ray spectrum (left); same spectrum in the region of the K$_\alpha$ standard and violating transitions in Pb (right).

The p value (probability of having measured an excess with respect to b in the two ROIs):

$$p = \sum_{j=z_1+1}^{\infty} \frac{b^{z_1}}{z_1!} \exp(-b) \sum_{j=z_2+1}^{\infty} \frac{b^{z_2}}{z_2!} \exp(-b) = \left[1 - \sum_{j=0}^{z_1} \frac{b^{z_1}}{z_1!} \exp(-b) \right] \left[1 - \sum_{j=0}^{z_2} \frac{b^{z_2}}{z_2!} \exp(-b) \right]$$

p = 0.012 corresponding to 2.3 standard deviations.

preliminary

$$\frac{1}{2}\beta^2 < 2.75 \cdot 10^{-44}$$

**M. Veith bechelor thesys
La Sapienza**

Dissemination

Papers & organized events
Oct. 2018 – Mar. 2019

The following papers were prepared/accepted/submitted for publication:

- **Search for the violation of Pauli Exclusion Principle at LNGS, VIP-2 Collaboration, EPJ Web Conf. 182 (2018) 02118**
- **Detector setup of the VIP2 underground experiment at LNGS, accepted in NIM A (arXiv:1807.02182)**
- **High precision test of the Pauli Exclusion Principle for electrons, submitted to MDPI Condensed Matter**
- **Search for a remnant radiation of the Pauli Exclusion Principle in a Roman Lead block, to be submitted to Entropy**
- **VIP-2 at LNGS: testing the Pauli Exclusion Principle, submitted to Journal of Physics: Conference Series**
- **Vip-2 underground experiment as a Crash-Test of Non-Commutative Quantum Gravity – in preparation**

Events Organization:

1) *New Quantum Horizons: From Foundations To Biology,* **https://agenda.infn.it/event/17043/**

2) The second day of the workshop: *Low-energy strangeness studies at DAFNE and J-PARC, 19-20 December 2018, LNF-INFN, Frascati,* **https://agenda.infn.it/event/17672/   was dedicated to VIP and related items**

3) 22 February 2019: meeting on theoretical interpretation of VIP results at LNF-INFN with Fudan Univ. colleagues, followed by a Skype Conference on 13th March.

Dissemination Oct. 2018 – Mar. 2019

The VIP2 experiment was presented in a series of Workshops and Conferences, as well as public events, as follows:

1) K. Piscicchia: Quantum foundation tests at Gran Sasso underground laboratory, New quantum horizons, from foundations to biology, LNF (INFN) Frascati 15-16 November 2018

2) K. Piscicchia, Testing Dynamical Reduction Models at the Gran Sasso underground laboratory, Discrete Symmetries in Particle, Nuclear and Atomic Physics and implications for our Universe, ECT* - October 8-12, 2018, Trento, Italy

3) K. Piscicchia, Testing spin statistics at Gran Sasso underground laboratory, DISCRETE2018, Austrian Accademy of Science, 26-30 November 2018, Vienna, Austrian

4) K. Piscicchia, High precision tests of the Pauli Exclusion Principle, status and future perspectives, High Precision X-ray Measurements 2018, 17-19 October 2018, LNF (INFN) (Italy)

5) K. Piscicchia, X and gamma rays spectroscopy, experimental probes for Quantum Mechanics foundations, Low-energy strangeness studies at DAFNE and J-PARC, 19-20 December 2018, LNF-INFN

6) C. Curceanu "Stars and Cats: from exotic atoms studies to impossible atoms hunting to explore the Universe", Colloquium at University of Adelaide (Australia), 7 Dec, 2018

7) C. Curceanu "Testing Quantum Mechanics Underground: a hunt of the "impossible" Radiation", Colloquium at Pavia Univ., 21 March 2019

8) J. Marton: VIP2 in LNGS – Testing the Pauli Exclusion Principle for electrons with high sensitivity, DICE 2018 International Conference Spacetime-Matter-Quantum Mechanics, Casteliglioncello, Italy, September 17-21, 2018

9) A. Pichler: New results on the search for the violation of the Pauli Exclusion Principle for electrons from VIP2 experiment, LNGS Seminar, Thursday 08 Nov 2018

- 6 talks in schools and public.

Other info:

- C. Curceanu together with Stephen L. Adler of the Institute for Advanced Study of Princeton, won the Fundamental Physics Innovation Award of the American Physics Society, Gordon and Betty Moore Foundation, for an innovative research project in the field of quantum physics.

- KP staff Centro Fermi based on the activity on VIP.

Future plans
VIP-2 setup (open system)

- Finalize and submit for publication the papers on data analyses up to now (at least 1 paper)

- Optimization of the new veto system (lower threshold – about 50 keV) and installation inside the setup within end of spring 2019

- Data taking for 2.5 years -> estimate gain factor 15 from statistics, 5-10 from background, 1.2 – 1.5 from higher current (new cryognic system for target, for a total of 15-20 in beta**2/2 with VIP-like analysis

- Refined statistical data analyses continued
- Refined calculation electrons path inside bulk material
- Continuation of Monte Carlo simulations and studies for optimization of the run

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Future plans
VIP-Lead and other materials
(closed systems)

- **Finalize and submit for publication the paper on theoretical interpretation and VIP-lead results (at least 1 paper)**

- **Refined data analyses for additional targets: V, Pt, Hf, Ta /existent) and study of the limit of PEP-violation on various materials 10**-45 for non-commutative space-time models**

- **Intensive collaboration with theoreticians (in particular with Addazi and Marianò) for the interpretation of the VIP-results**

- **Studies in Frascati laboratory of a possible setup to test anisotropy effects – quantum-gravity tests**

- **Dissemination activities: presentation of the VIP-2 results in at least 3 events (Workshops/conferences) and in Dissemination events – such as Open Labs (May 2019) and in talks/seminars at schools.**

Acknowledgements:
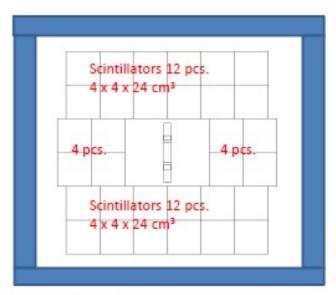
Thank you!

Experimental setup and Monte Carlo model

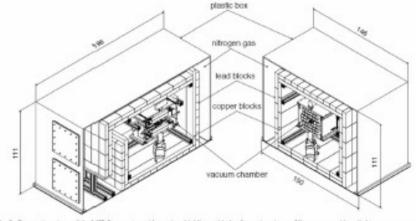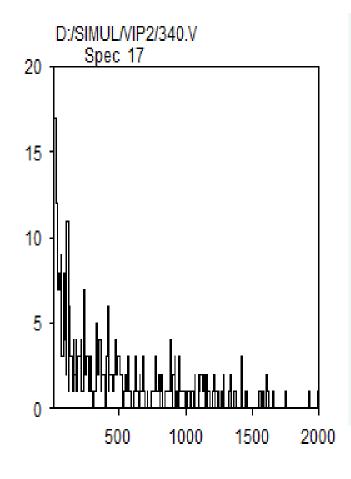**scheme** of the setup with plastic scintillators as active shielding

Fig. 3 Perspective views of the WIP-2 apparatus with passive shielding, with the dimensions in cm. Nitrogen gas with a slight over pressure with respect to the outside air will be circulated inside the plastic shielding.

new setup 2018
2 modules of 3.2 x 1.6 cm² (4x2 cells) SDDs on each side, each 500 μm thick
Cu: 2.0 x 9.0 cm²   25 μm thick

passivly shielded setup.

deposited energy dE in the **active shielding scintillators**

IF a signal in the SDDs was detec'd

D:/SIMUL/VIP2/340.V
Spec 17
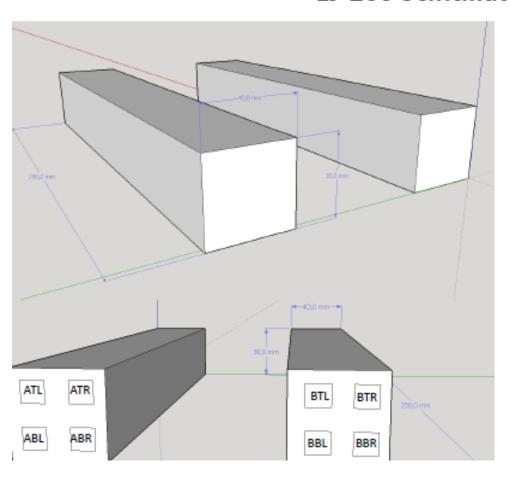
Scintllator threshold:

**if thres. about 50 keV:
50% suppression**

**if thresh. about 300-400 keV:
25% suppression**

EJ-200 Scintillator bars

- Scintillator EJ-200 bar dimension: (250 x 38 x 40) mm^3

- Each single output is made by 2 SiPMs in series.

- No light guides.

- 4 outputs for each scintillator bar.
    - ATL: Scintillator A, Top Left
    - ATR: Scintillator A, Top Right
    - ABL: Scintillator A, Bottom Left
    - ABR: Scintillator A, Bottom Right
    - BTL: Scintillator B, Top Left
    - BTR: Scintillator B, Top Right
    - BBL: Scintillator B, Bottom Left
    - BBR: Scintillator B, Bottom Right

Experimental setup for EJ-200 scintillator characterization
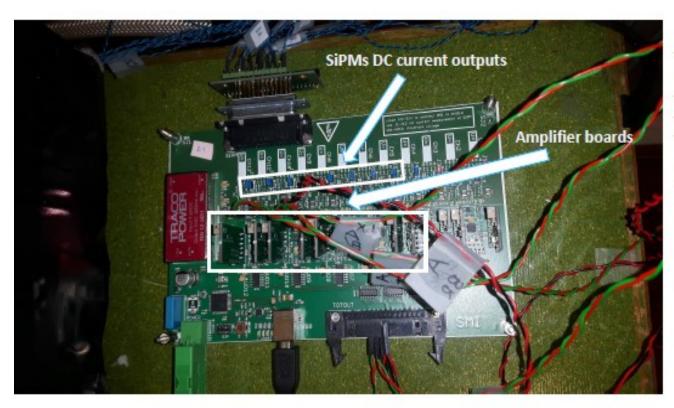
Black box, light tight
for Scintillator bars

Black box, light tight
for Scintillator bars
+
Readout board

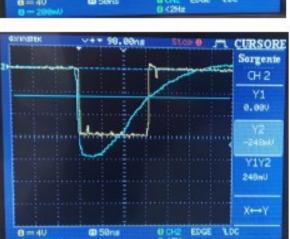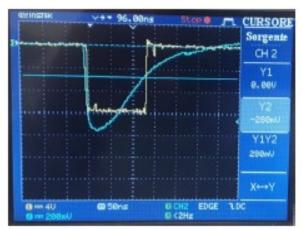# Gain: SiPMs DC current regulation (Coarse Gain)

The DC current of each single channel has been tuned through its related trimmer on the amplifier board.
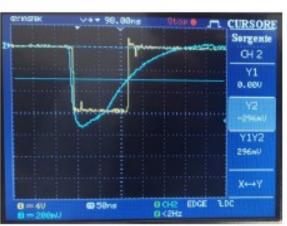
The current output for all the 8 channels has been set to the same value for all the channels.

ToT: Threshold settings (scope)

Example of the response in terms of analog and digital (ToT) outputs for 4 different channels:
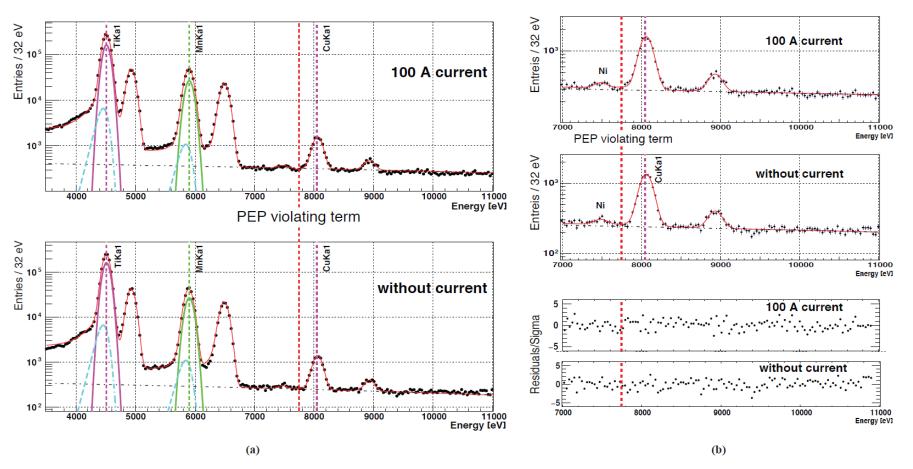ATR, ABR, BTR, BBR.

Gain set to 3000 (= 12,1 uA)

Threshold set to 2500 (= -300 mV)

As can be seen from the scope, the waveforms are quite uniform for all the SiPMs

Blue: Analog output
Yellow: Digital output (Time over Treshold)

New refined data anlysis (same data set) - simultaneous fit of the "sig + bkg" and bkg spectra, in order to use all the information available for the background shape from the data. The obtained fits:

(a)

(b)

Fig. 8 A global chi-square function was used to fit simultaneously the spectra with and without 100 A current applied to the copper conductor. The energy position for the expected PEP violating events is about 300 eV below the normal copper $K_{\alpha 1}$ transition. The Gaussian function and the tail part of the $K_{\alpha 1}$ components and the continuous background from the fit result are also plotted. (a) : the fit to the wide energy range from 3.5 keV to 11 keV; (b) : the fit and its residual for the 7 keV to 11 keV range where there is no background coming from the calibration source.

Improved limit on PEP violation probability:

$$\frac{\beta^2}{2} \leq \frac{3 \times 67}{6.0 \times 10^{30}} = 3.4 \times 10^{-29}$$

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Experimental search for the violation of Pauli exclusion principle

VIP-2 Collaboration

New paper recently submitted to   ENTROPY

MDPI

On the importance of electron diffusion in a bulk-matter test of the Pauli Exclusion Principle

Edoardo Milotti[1,*], Sergio Bartalucci[2], Sergio Bertolucci[3], Massimiliano Bazzi[2], Mario Bragadireanu[2,4], Michael Cargnelli[2,5], Alberto Clozza[2], Catalina Curceanu[2,4,6], Luca De Paolis[2], Jean-Pierre Egger[7], Carlo Guaraldo[2], Mihail Iliescu[2], Matthias Laubenstein[8], Johann Marton[2,5], Marco Miliucci[2], Andreas Pichler[2,5], Dorel Pietreanu[2,4], Kristian Piscicchia[2,6], Alessandro Scordo[2], Hexi Shi[9], Diana Laura Sirghi[2,4], Florin Sirghi[2,4], Laura Sperandio[2], Oton Vazquez Doce[2,10], Eberhard Widmann[5] and Johann Zmeskal[2,5]

The random walks of the electrons as they move from the entrance to the exit of the copper sample is fully described in terms of a diffusion transport model.

VIP-2 final setup gain factors

	VIP	VIP2	Gain
acceptance	1 %	7.7 %	~8
current	40 A	100 A	~2
X ray detection efficiency	0.4	0.99	~Sqrt(2)
Energy resolution @ 8 keV	~350 eV	~190 eV	~Sqrt(4)
Reduced active area	114 cm^2	20 cm^2	~Sqrt(6)
Passive Shielding	Yes	No (Yet)	~Sqrt(0.1)

+ MC simulations (preliminary) passive shielding contribution to the background reduction ~ sqrt(10)

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 Multipole order	Initial en.	Final en.	Transition energy	Radiative transition rate (s-1)	
$2p_{1/2}$ - $1s_{1/2}$ E1	-45799	-53528	**7729**	2.63E+14	} K_α
$2p_{3/2}$ - $1s_{1/2}$ E1+M2	-45780	-53528	**7748**	2.56E+14	} K_β
$3p_{1/2}$ - $1s_{1/2}$	-44998	-53528	**8530**	2.78E+13	E1
$3p_{3/2}$ - $1s_{1/2}$ E1+M2	-44996	-53528	**8532**	2.68E+13	

Normal copper: ~ <u>8050</u> eV (2p → 1s)

Note: similar value obtained by S. Di Matteo e L. Sperandio in the "sudden approximation" – preprint LNF

this β can be simply related to the q parameter of the quon theory of Greenberg and Mohapatra

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

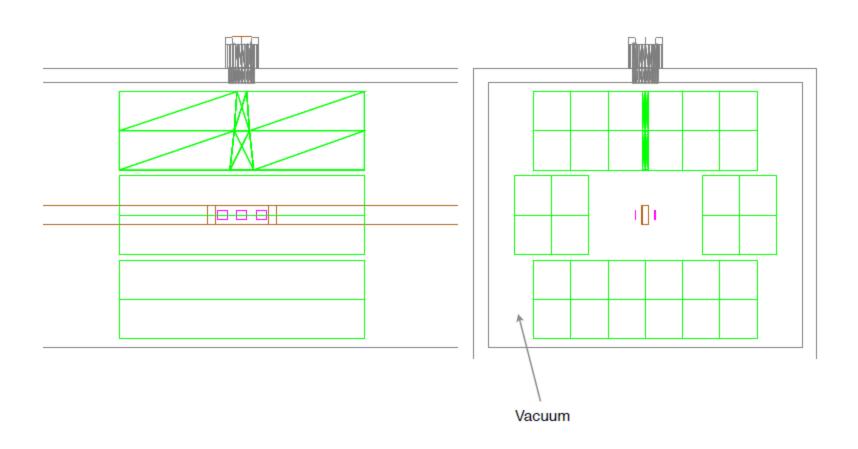quon algebra is a sort of weighted average between fermion and boson algebra:

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

or also

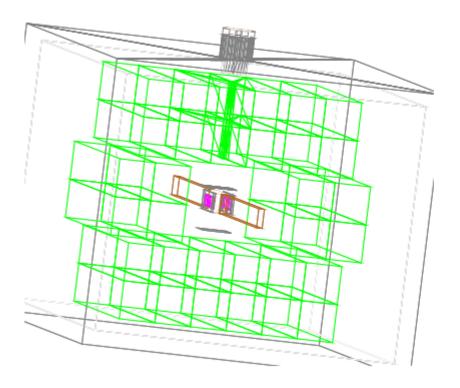$$a_k a_l^+ - q a_l^+ a_k = \delta_{kl}$$

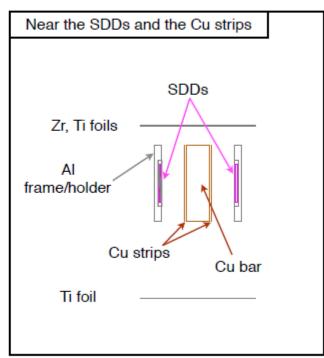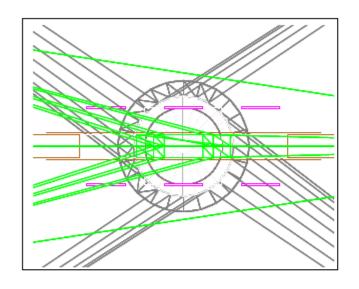# MC simulation with Geant4.10

Geometry - MC

Vacuum

Geometry - MC

Near the SDDs and the Cu strips

SDDs

Zr, Ti foils

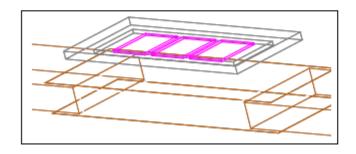Al frame/holder

Cu strips

Cu bar

Ti foil

SDDs - MC

Assembly : 3 on one side ;
other side by transform3D
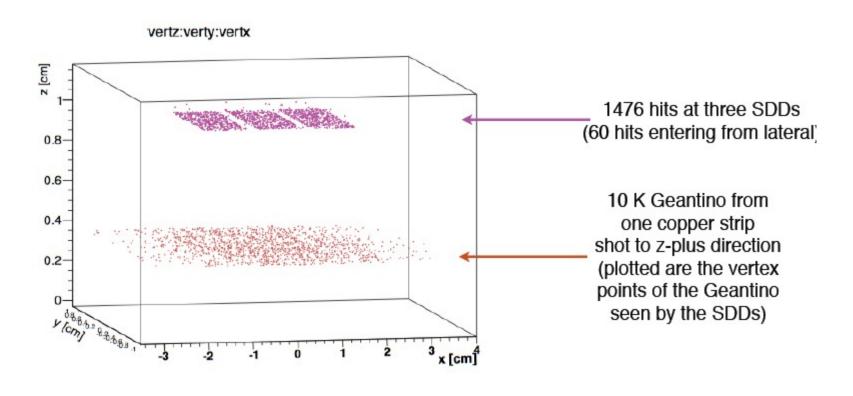rotateY by 180 degree,
AddPlacedVolume to the
assembly

Dimension of single SDD:
surface area :1 cm2;
thickness :450 um.

* Efficiency of SDD > 90% up to 10 keV

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1. Geantino run
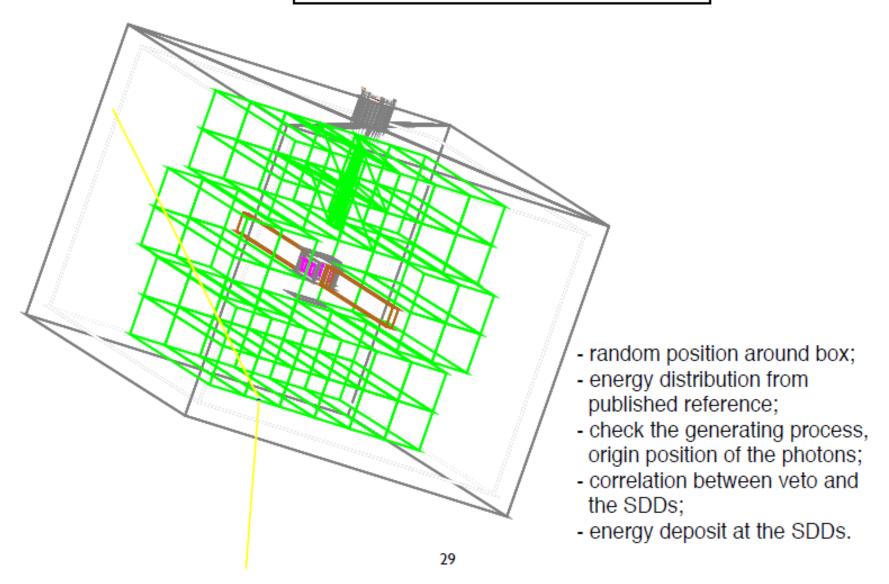
to estimate solid angle acceptance

vertz:verty:vertx

1476 hits at three SDDs
(60 hits entering from lateral)

10 K Geantino from
one copper strip
shot to z-plus direction
(plotted are the vertex
points of the Geantino
seen by the SDDs)
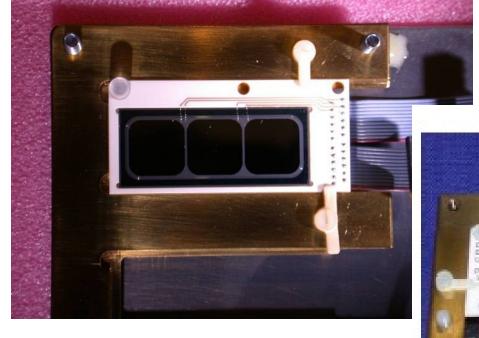
**solid angle acceptance :
14.7 ± 0.4 %**

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2. Gamma source run

veto efficiency and background estimation

- random position around box;
- energy distribution from
  published reference;
- check the generating process,
  origin position of the photons;
- correlation between veto and
  the SDDs;
- energy deposit at the SDDs.

SDD detectors (used by SIDDHARTA) 40% active array

2 arrays of 1 x 3 SDDs 3 cm²

liquid argon closed circuit cooling - 170 °C

Pauli Exclusion Principle (PEP)

Several proofs exist in QFT which differ in clarity and quality of physical insight.

Proof of spin-statistics theorem by Lüders and Zumino

Postulates:

1 - The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)

2 - Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality – microcausality)

3 - The vacuum is the state of lowest energy

4 - The metric of the Hilbert space is positive definite

5 - 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)

Effective field theories of PEP violation

Ignatiev & Kuzmin model: Fermi oscillator with a third state

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

$\boldsymbol{\beta}$ *quantifies the degree of violation in the transition* $|1\rangle \;\rightarrow\; |2\rangle$

Greenberg, O.W.; Mohapatra, R.N. $a_k a_l^+ - q a_l^+ a_k = \delta_{k,l}$

Local Quantum Field Theory, *q* parameter deforms anticommutators, <u>quon theory</u>

A. M. L. Messiah and O. W. Greenberg, Phys. Rev. 136 (1964) B248.

O. W. Greenberg and A. M. L. Messiah, Phys. Rev. 138 (1965) B1155.

G. Gentile, NuovoCimento 17, 493(1940)

H. S. Green, Phys. Rev. 90 (1953) 270.

A. Y. Ignatiev and V. A. Kuzmin, JETP Lett. 47 (1988) 4.

V. N. Gavrin, A. Y. Ignatiev and V. A. Kuzmin, Phys. Lett. B 206 (1988) 343.

O.W. Greenberg, Phys. Rev. Lett. 64, 705 (1990)

R.N. Mohapatra, Phys. Lett. B 242, 407 (1990)

O.W.Greenberg, R.C.Hilborn, Fund.Phys.29, 397(1999)