Open Problems in Quantum Mechanics (PAMQ)

Coordinator:

Catalina Curceanu, LNF-INFN and Associated to Centro Fermi

Participants:

Kristian Piscicchia, grant CF, Feb 2016 – Feb 2019

Place of Work & Collaborations:

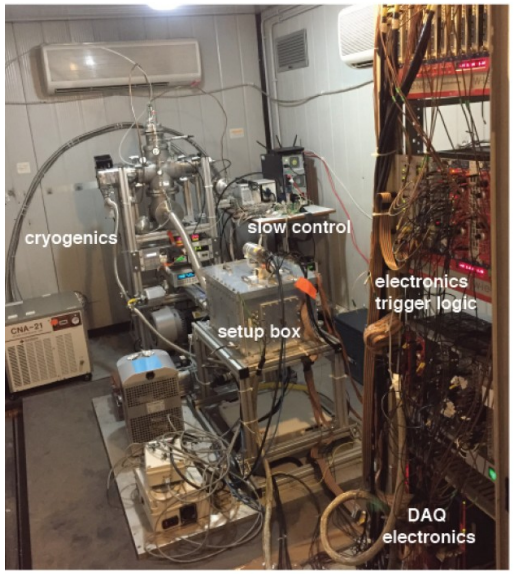
LNF-INFN
LNGS-INFN
Univ. Trieste
Univ. Bologna
SMI-OeAW, Vienna (Austria)
Univ. Vienna (Austria)
IFIN-HH Bucharest (Romania)
Wigner Institute (Hungary)
Rennes Univ. (France)
Stephen Adler- Inst. For Advanced Study, Princeton, USA
Univ. Melbourne (Australia)
Fudan University, Shanghai (China)

Open Problems in Quantum Mechanics (PAMQ)

PAMQ deals in particular with:

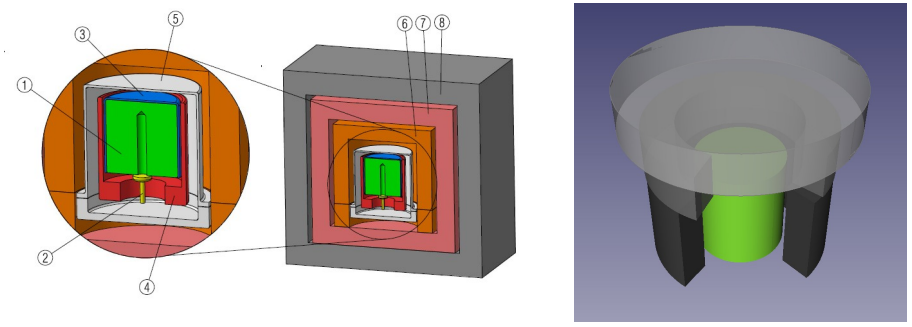
- Tests of the Pauli Exclusion Principle for electrons, the VIP-2 experiment at Gran Sasso Underground Laboratory

- The *measurement problem* → searching for signal of spontaneous radiation emission predicted in Dynamical Reduction Models of the wave function collapse (Continuous Spontaneous Localization CSL & Diosi-Penrose)



The VIP2 setup in data taking

FIG. 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*



Two setups based on HPGe detectors operated In four data taking periods (45 days each) at LNGS

Open Problems in Quantum Mechanics (PAMQ)

The VIP-2 experiment, scientific case

Feynman Lectures on Physics (100 years from his birth):

"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."

Open Problems in Quantum Mechanics (PAMQ)

- *Theories of Statistics Violation*

  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) …

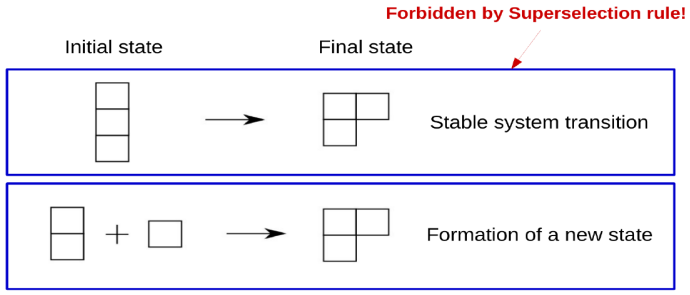
noncommutative spacetime" → *intense collaboration started this year with the th. Group leaded by A. Marcianò (Fudan University, China)*

- **Ignatiev & Kuzmin model: Fermi oscillator with a third state, β quantifies the degree of violation in the transition $|1> \rightarrow |2>$**

- **O. W. Greenberg, R. N. Mohapatra, Phys. Rev. Lett. (1987), 59 2507 → quon theory**

- **Messiah – Greenberg superselection rule : transition probability between two different symmetry states is ZERO**

VIP is the sole experiment respecting the M-G superselection rule →



TESTING VIOLATIONS OF THE PAULI EXCLUSION PRINCIPLE INDUCED FROM NON-COMMUTATIVE SPACE-TIME

Andrea Addazi,
Fudan University, Shanghai.

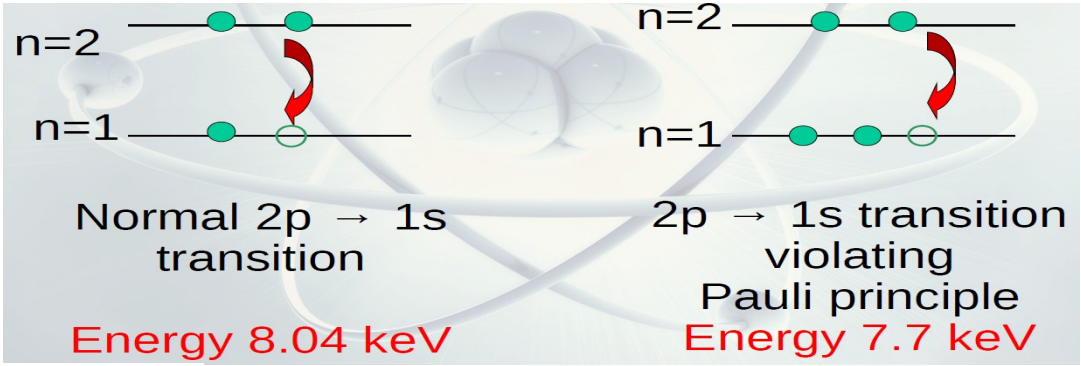
in collaboration with A. Marcianò (Fudan),

We propose underground experiments!!!

Claim:
Pauli Exclusion principle violations induced from quantum gravity can be tested

Open Problems in Quantum Mechanics (PAMQ)

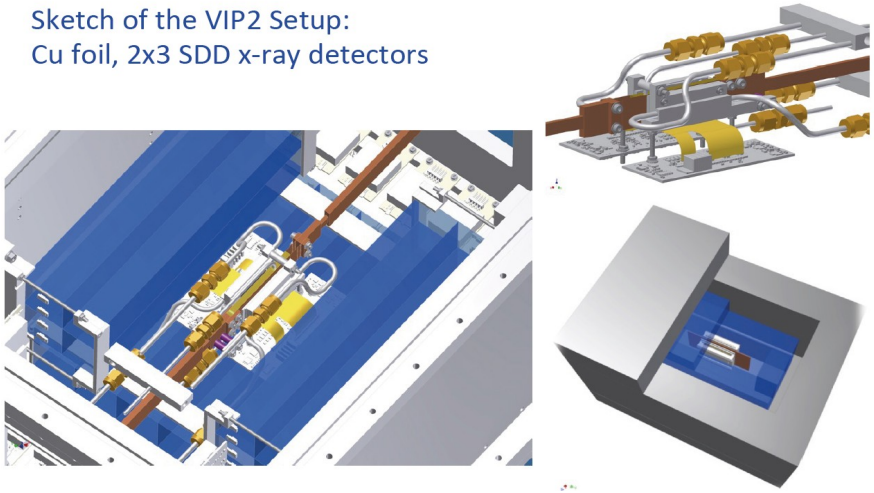
VIP experimental method: search for anomalous X-ray transition, from current e^- in radio-pure Cu target



BKG reference spectrum acquired with current off

VIP result : $\beta^2/2 < 4.7\ 10^{-29}$

Sketch of the VIP2 Setup:
Cu foil, 2x3 SDD x-ray detectors



From VIP to VIP-2 :

- CCDs → SDDs better resolution (190 keV @ 8keV) and triggerable
- VETO system: plastic scintillators read by SiPMs
- higher acceptance
- Cu strips cooled by a closed Fryka chiller circuit → higher current (100 A) @ 20 °C of Cu target implies 1 °K heating in SDDs
- fast calibration system
- new shielding

VIP-2 goal 2 OM improvement

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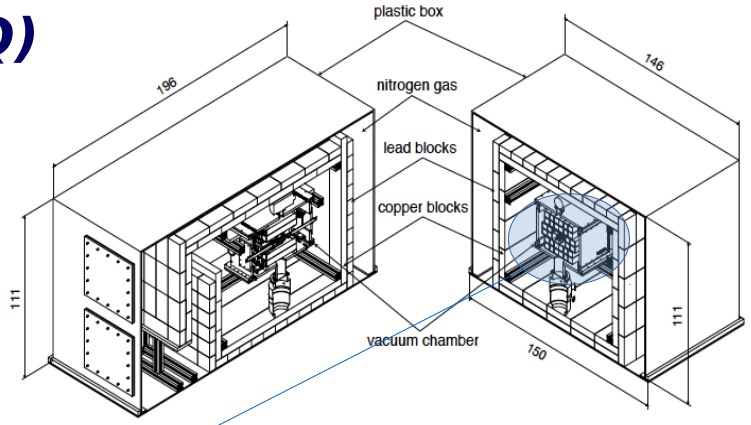
VIP-2 final configuration

recently finalized the passive shielding configuration (layers of copper and lead)



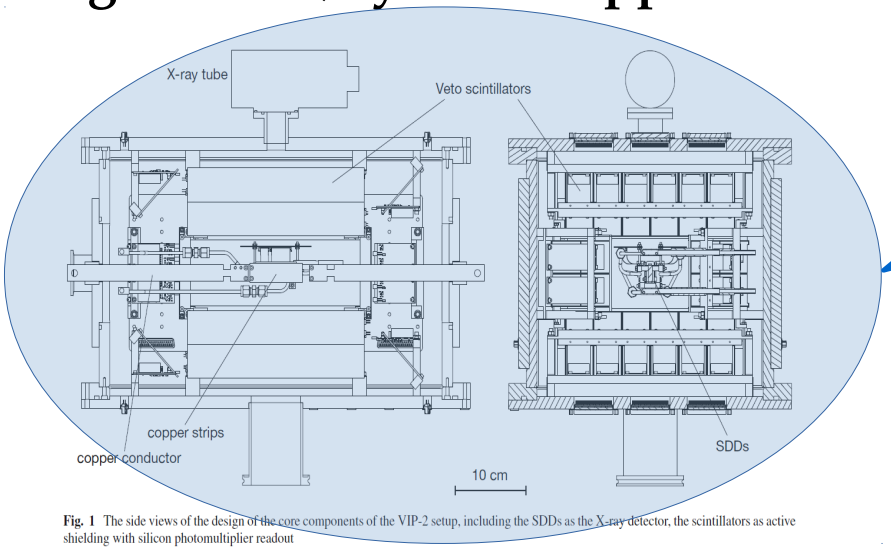


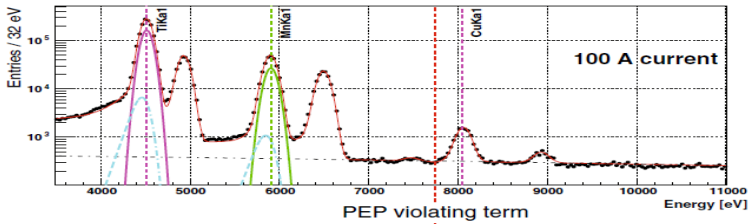
Fig. 1 The side views of the design of the core components of the VIP-2 setup, including the SDDs as the X-ray detector, the scintillators as active shielding with silicon photomultiplier readout

VIP-2 already achieved good results:

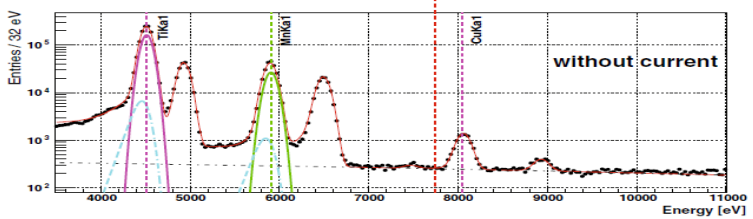
with the preliminary acquired data set, without shielding

$$\frac{\beta^2}{2} \leq \frac{3 \times 82}{1.46 \times 10^{31}} = 1.69 \times 10^{-29}$$

factor 3 better than VIP



PEP violating term



Global likelihood constructed using the spectrum with current + reference bkg spectrum

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VIP-2 already achieved good results:

published result with a subset of the whole pre-VIP-2 data. Second paper in preparation with the whole statistics.

Eur. Phys. J. C (2018) 78:319
https://doi.org/10.1140/epjc/s10052-018-5802-4

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Experimental Physics

Experimental search for the violation of Pauli exclusion principle

VIP-2 Collaboration

Big effort also devoted to model the electron diffusion process across the target:

Entropy **2018**, *20*(7), 515; https://doi.org/10.3390/e20070515

Open Access Article

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

Random walks of the electrons described in terms of a diffusion transport model ($\beta^2/2 < 2.6\ 10^{-40}$).

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Experimental tests of the Dynamical Reduction Models:

- CSL – non-linear and stochastic modification of the Schrödinger equation …

$$d|\psi_t\rangle = \left[-\frac{i}{\hbar}H\,dt + \sqrt{\lambda}\int d^3x(N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t)dW_t(\mathbf{x}) - \frac{\lambda}{2}\int d^3x(N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t)^2 dt\right]|\psi_t\rangle$$

System's Hamiltonian — NEW COLLAPSE TERMS → New Physics

λ - collapse rate

$r_c \sim 10^{-16}$ m – correlation length

measures the strength of the collapse

strongly debated, see e. g. S. L. Adler, JPA 40, (2007) 2935
Adler, S.L.; Bassi, A.; Donadi, S., JPA 46, (2013) 245304.

- Diosi – Penrose – gravity related collapse model …

system is in a quantum superposition of two different positions → superposition of two different space-times is generated → the more massive the superposition, the faster it is suppressed.

The model characteristic parameter R_0 prediction ~ 1 fm

Open Problems in Quantum Mechanics (PAMQ)

both models induce a diffusion motion for the wave packet →

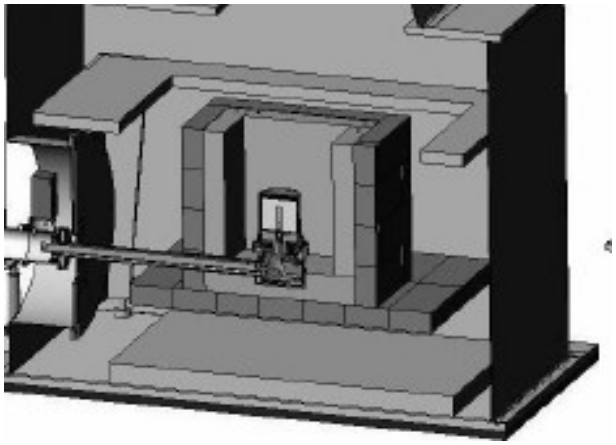
spontaneous emission

- CSL – spontaneous photons emission rate:

$$\frac{d\Gamma'}{dE} = \left\{ \left(N_p^2 + N_e \right) \cdot \left(N_a \, T \right) \right\} \frac{\lambda \hbar e^2}{4\pi^2 \varepsilon_0 c^3 m_0^2 r_C^2 E}$$

- Diosi – Penrose – spontaneous photons emission rate: $\frac{d\Gamma_t}{d\omega} = \frac{2}{3} \frac{G e^2 N^2 N_a}{\pi^{3/2} \varepsilon_0 c^3 R_0^3 \omega},$

HPGe detector based experiment @ LNGS



- active HPGe detector surrounded by 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 radon.

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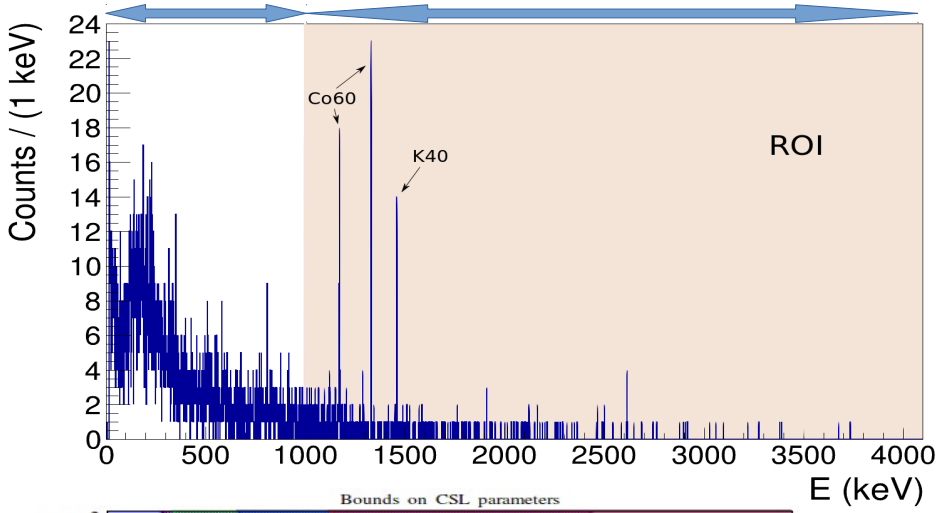
HPGe detector based experiment @ LNGS

cosmic rays, bremsstrahlung from ^{210}Pb & daughters

Region Of Interest ΔE=(1000 – 3800)keV compatible with theretical constrains



three months data taking with 2kg Germanium active mass

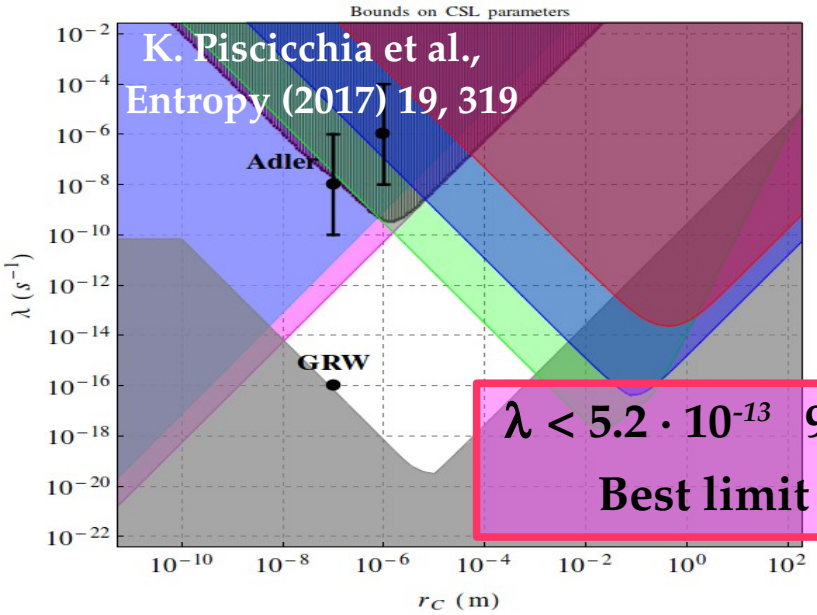
↓

the pdf of the models parameters is obtained within a Bayesian model:

$$\tilde{p}\left(\Lambda_c | p(z_c|\Lambda_c)\right) = \frac{\Lambda_c^{z_c}\, e^{-\Lambda_c}\, \theta(\Lambda_c^{max} - \Lambda_c)}{\int_0^{\Lambda_c^{max}} \Lambda_c^{z_c}\, e^{-\Lambda_c}\, d\Lambda_c}$$

$R_0 > 0.54 \times 10^{-10}$ m 95% C. L.

Diosi – Penrose model Rouled out!



λ < 5.2 · 10^{-13} 95% C. L.

Best limit ever

Open Problems in Quantum Mechanics (PAMQ)

HPGe detector based experiment @LNGS

three months data taking with
2kg Germanium active mass

Submitted last week to Science

Test of gravity-induced wave function collapse

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Matthias Laubenstein,[4] Angelo Bassi,[5,6]

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Piazza del Viminale 1, 00184 Rome, Italy.
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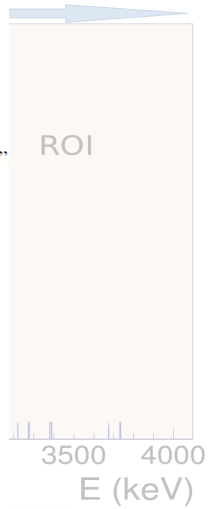
Via Enrico Fermi 40, 00044 Frascati (Italy).
[4]Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare,
Via G. Acitelli 22, 67100 Assergi, Italy.
[5]Department of Physics, University of Trieste,
Strada Costiera 11, 34151 Trieste, Italy.
[6]Istituto Nazionale di Fisica Nucleare, Trieste Section,
Via Valerio 2, 34127 Trieste, Italy.

*To whom correspondence should be addressed; E-mail: sandro.donadi@uni-ulm.de.

Penrose proposed that a spatial quantum superposition collapses as a backreaction from spacetime, which is curved in different ways by each branch of the superposition; in this sense, one speaks of gravity-induced wave function collapse. He also provided a heuristic formula to compute the decay time of the superposition, which is equivalent to that suggested earlier by Diósi, hence the name Diósi-Penrose model. The collapse is random, and this randomness shows up as a Brownian motion of the particles in any system resulting, if charged, in an emission of a spontaneous radiation. We computed the emis-

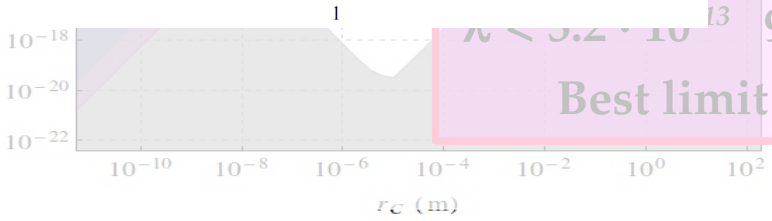


the pdf of the models parameters is obtained within a Bayesian model:

$$\tilde{p}\left(\Lambda_c | p(z_c|\Lambda_c)\right) = \frac{\Lambda_c^{z_c}\, e^{-\Lambda_c}\, \theta(\Lambda_c^{max} - \Lambda_c)}{\int_0^{\Lambda_c^{max}} \Lambda_c^{z_c}\, e^{-\Lambda_c}\, d\Lambda_c}$$

$R_0 > 0.54 \times 10^{-10}$ m 95% C. L.

Diosi – Penrose model
Rouled out!

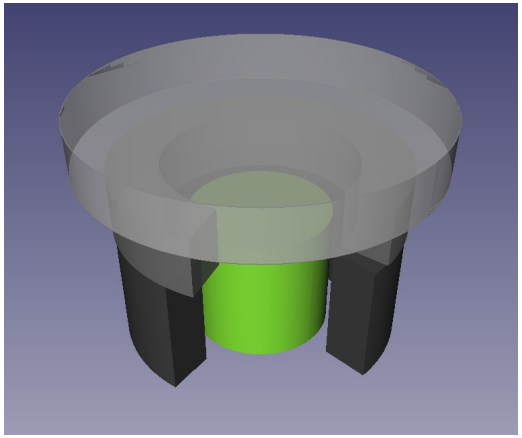


95% C. L.
Best limit ever

Open Problems in Quantum Mechanics (PAMQ)

Complementarity of the two experiments:

Improved setup : HPGe detector surrounded by radiopure roman Pb target.



Optimized to further improve the limit on λ

↓

data was re-analysed this year to constrain the PEP violation probability in Pb.

$$\frac{1}{2}\beta^2 < 1.58 \cdot 10^{-40}$$

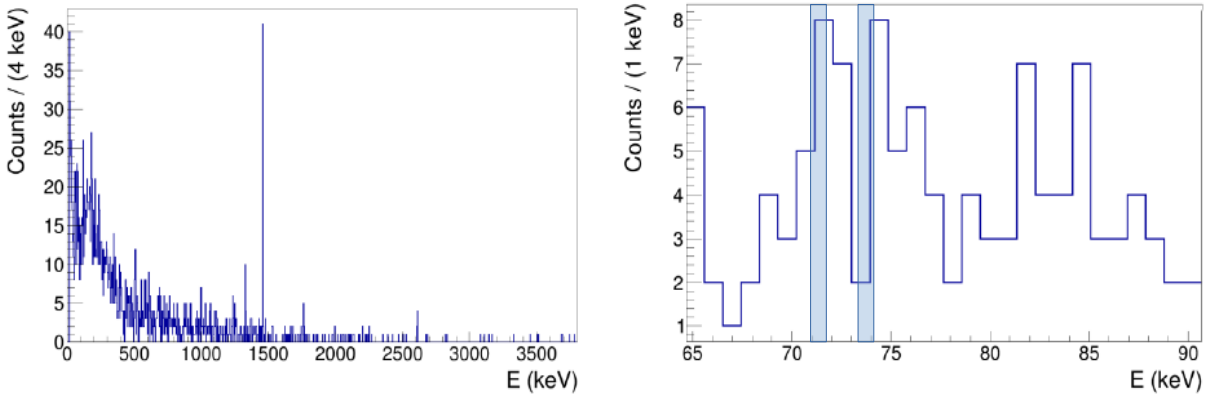


Figure 1. Total measured X-ray spectrum (left); same spectrum in the region of the K_α standard and violating transitions in Pb (right).

Factor 16 better then Found Phys (2012) 42, 1015
Paper in preparation
to be submitted to Entropy

Open Problems in Quantum Mechanics (PAMQ)

2018 milestones, scientific activity:

1) Data taking with VIP-2 and publication of new results – best limit on PEP violation probability → 100% VIP-2 setup completed, data taking ongoing, 2 papers published (Eur. Phys. J. C & Entropy) + 1 in press + 1 conf. Proc

2) Publication of the results of the data analyses for collapse models for Ge dedicated data taking in high-impact peer-reviewed journal → 90% paper completed and submitted to Science + 1 conf proc

3) Detector development and new data taking for study of collapse models and PEP violation → 100% setup with HPGe + Pb (high radiopurity roman Pb target) prepared and data taking in August – Sept 2018 at LNGS; data analyses undergoing

4) Organization of a workshop on quantum foundation and quantum technologies
New directions of quantum investigations: quantum technologies, quantum medicine… → 100% 2 workshops financed by Centro Fermi in the context of PAMQ + 1 workshop sponsored by Centro Fermi

Open Problems in Quantum Mechanics (PAMQ)

2018 milestones, scientific activity:

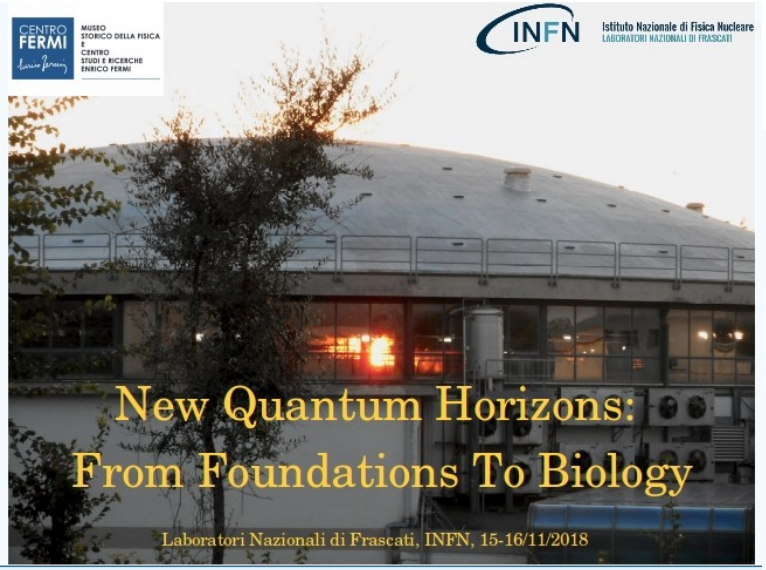
Total number of papers published in 2018 : 12 + 3 in publication + 1 submitted

Total number of attended conferences in 2018 : 14 (10 invited talks) + 1 colloquium

1 Bachelor degree thesis (at La Sapienza University) on VIP ongoing

Open Problems in Quantum Mechanics (PAMQ)

WORKSHOPS:



15-16 November 2018 *Laboratori Nazionali di Frascati INFN*
Europe/Rome timezone

2-5 July 2018 *Laboratori Nazionali di Frascati INFN*
Europe/Rome timezone

19-20 December 2018 *Laboratori Nazionali di Frascati, INFN*
Europe/Rome timezone

Open Problems in Quantum Mechanics (PAMQ)

WORKSHOPS:

Open Problems in Quantum Mechanics (PAMQ)

Dissemination activity in 2018:

- PAMQ activities were presented at the international school INSPYRE 2018 and at the TEDxCluj event, Brasov (Romania) , 24 Febbraio 2018.

- In 8 talks at Italian high schools the PAMQ activities were included.

- 8 talks were given in Australia, in universities and high schools, concerning the PAMQ project

awards 2018:

C. Curceanu - "Distinguished Sir Thomas Lyle Fellowship"
https://www.centrofermi.it/it/news/123-catalina-curceanu-vince-il-premio-distinguished-sir-thomas-lyle-fellowship
C. Curceanu - "100 per il Centenario"
https://www.centrofermi.it/it/news/116-catalina-curceanu-vincitrice-del-premio-100-per-il-centenario
C. Curceanu – Romanian Republic Knight for Scientific Merits,
https://www.frascatiscienza.it/2018/10/catalina-curceanu-cavaliere-della-romania/
C. Curceanu, "George Southgate Fellowship", Univ. Adelaide
C. Curceanu - Fundamental Physics Innovation award - dall' American Physics Society, Gordon and Betty Moore Foundation

Open Problems in Quantum Mechanics (PAMQ)

Complete list of publications in 2018:

K. Piscicchia et al., Phys.Lett. B782 (2018) 339-345

H. Shi, C. Curceanu, K. Piscicchia et al., Eur.Phys.J. C78 (2018) no.4, 319

E. Milotti, C. Curceanu, K. Piscicchia et al., Entropy 20 (2018) no.7, 515

K. Piscicchia et al., EPJ Web Conf. 166 (2018) 00020

A. Scordo, C. Curceanu, K. Piscicchia et al., EPJ Web Conf. 181 (2018) 01004

M. Skurzok, C. Curceanu, K. Piscicchia et al., Acta Phys.Polon. B49 (2018) 705

J. Marton, C. Curceanu, K. Piscicchia et al., Int.J.Mod.Phys.Conf.Ser. 46 (2018) 1860071

R. Del Grande, C. Curceanu, K. Piscicchia et al., EPJ Web Conf. 182 (2018) 02035

H. Shi, , C. Curceanu, K. Piscicchia et al., EPJ Web Conf. 182 (2018) 02118

K. Piscicchia et al., EPJ Web Conf. 181 (2018) 01005

K. Piscicchia et al., PoS CORFU2017 (2018) 201

K. Piscicchia et al., Acta Phys.Polon.Supp. 11 (2018) 609-616

Open Problems in Quantum Mechanics (PAMQ)

Next three years activity:

- **Preparation of setup and data taking for collapse models study at LNGS**

- **development of a new statistical model and Marcov Chain MC analysis for the collected data**

- **experimental activity in the context of the VIP-2 measurements**

- **interaction with the collaborating theoretical community (**Wigner Institute, Trieste Univ., Stephen Adler- Inst., Fudan University**) → feasibility study for new measurements**

- **study of new HAPG based detector systems for extremely high energy resolution radiation spectroscopy**

- **investigation of industrial and medichal applications of SDDs and HAPGs**

- **study of PAMQ implications on quantum technologies.**

- **Papers publication**
- **presentations at conferences**
- **organization of workshops and schools**
- **dissemination activity at LNF-INFN, schools, libraries, theaters ...**

Open Problems in Quantum Mechanics (PAMQ)

Milestones for 2019:

- **Publication of a peer-reviewed paper with new PEP violation probability limit based on the 2017/2018 VIP-2 collected data,**

- **data analysis and publication of a peer-reviewed paper concerning new limits on collapse models based on the dedicated measurements at LNGS with HPGe detectors in the context of PAMQ**

- **characterization and preparation of a test setup (HAPG based) for high precision radiation spectroscopy devoted to Quantum Foundational measurements**

- **Organization of a workshop on Quantum Foundation and applications in the context of the PAMQ project**

- **Dissemination and active participation to the CENTRO FERMI MUSEUM efforts.**

Open Problems in Quantum Mechanics (PAMQ)

Expected funding in the 3-year period:

- **Request of funding by Centro Fermi**
  - ***Assegno Ricerca junior : 2019 – 2021 : 70 kEuro***
  - ***Funds for organizing 3 workshops: 3 x 5 kEuro/year = 15 kEuro***
  - ***Travel expenses (missioni): 3 x 5 keuro/year = 15 keuro***
  - ***Consumables for the setups: 10 kEuro/year***
- **Co-funding in 3 years period (estimate)**
  - ***INFN: 100 kEuro (VIP)***
  - ***Austrian Scence Foundation and SMI-Vienna: 50 kEuro***
  - ***Others (IFIN-HH, Templeton, Trieste): 25 kEuro***
- **Potential external funding**
  - ***FQXI: 50 kEuro***
  - ***EU Funding (COST Actions, MCurie, FET,….): 100 kEuro***
  - ***Other nationals and internationals possible fundings: 50 kEuro***