High-precision tests of the Pauli Exclusion Principle in proton-nucleus interactions using the SPES Cyclotron

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For the VIP collaboration

International Workshop on future research program with the high power Cyclotron of SPES-LNL
12 - 13 May 2025

Basic idea of the proposal

The **Pauli Exclusion Principle (PEP)** is a **basic principle of quantum mechanics**, impacting whole science (physics, chemistry, biology…).

Small violations of PEP could point to **new physics beyond the Standard Model**. Previous work had focused on **electrons**; this study explores **nucleons**.

A **great opportuni**ty to perform such a measurement at the **high power Cyclotron of SPES-LNL**

Required for bosons.

$$\psi = \psi_1(a)\psi_2(b) \pm \psi_1(b)\psi_2(a)$$

Probability amplitude that both states "a" and "b" are occupied by electrons 1 and 2 in either order.

Required for fermions.

PEP lacks a clear, intuitive explanation

... Already in my original paper I stressed the circumstance that <u>I was unable to give a logical reason for the exclusion principle or to deduce it from more general assumptions</u>.

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 (50 years from his death – 15 december)

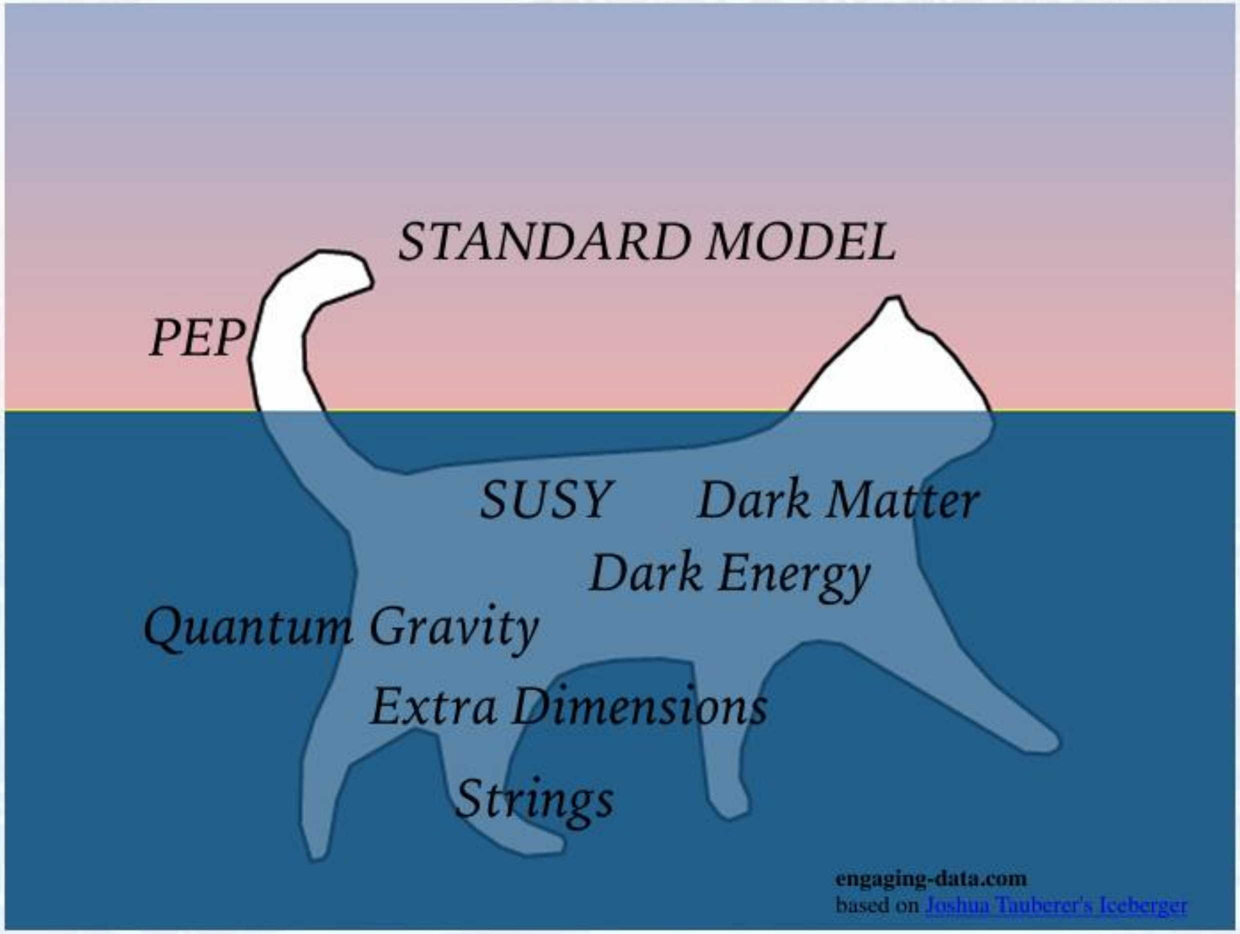
Theories of Violation of Statistics

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) 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."

The Pauli Exclusion Principle (PEP)



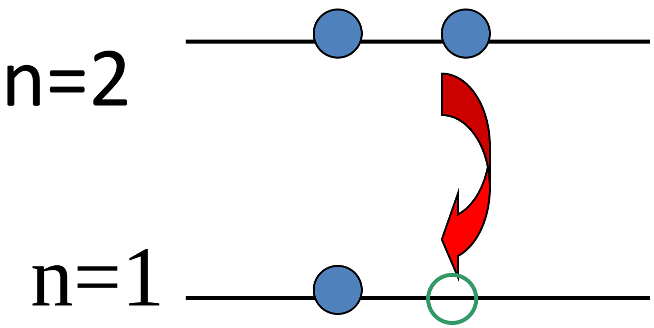
BSM theories embedding extra dimensions, non commutative and/or discrete spacetime could have effect on PEP

Within VIP we search for the impossible atoms

An experiment to test the Pauli Exclusion Principle (PEP) for electrons in a clean environment (LNGS) using atomic physics methods – the VIP experiment; here we want to extend this research to nucleons!

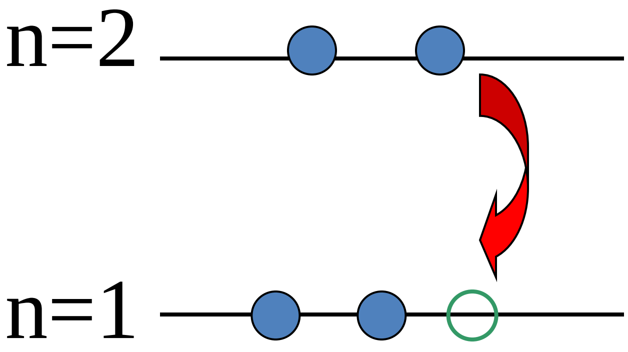
Experimental method:

Search for anomalous X-ray transitions when bringing “new” electrons (copper)



Normal 2p –>1s transition

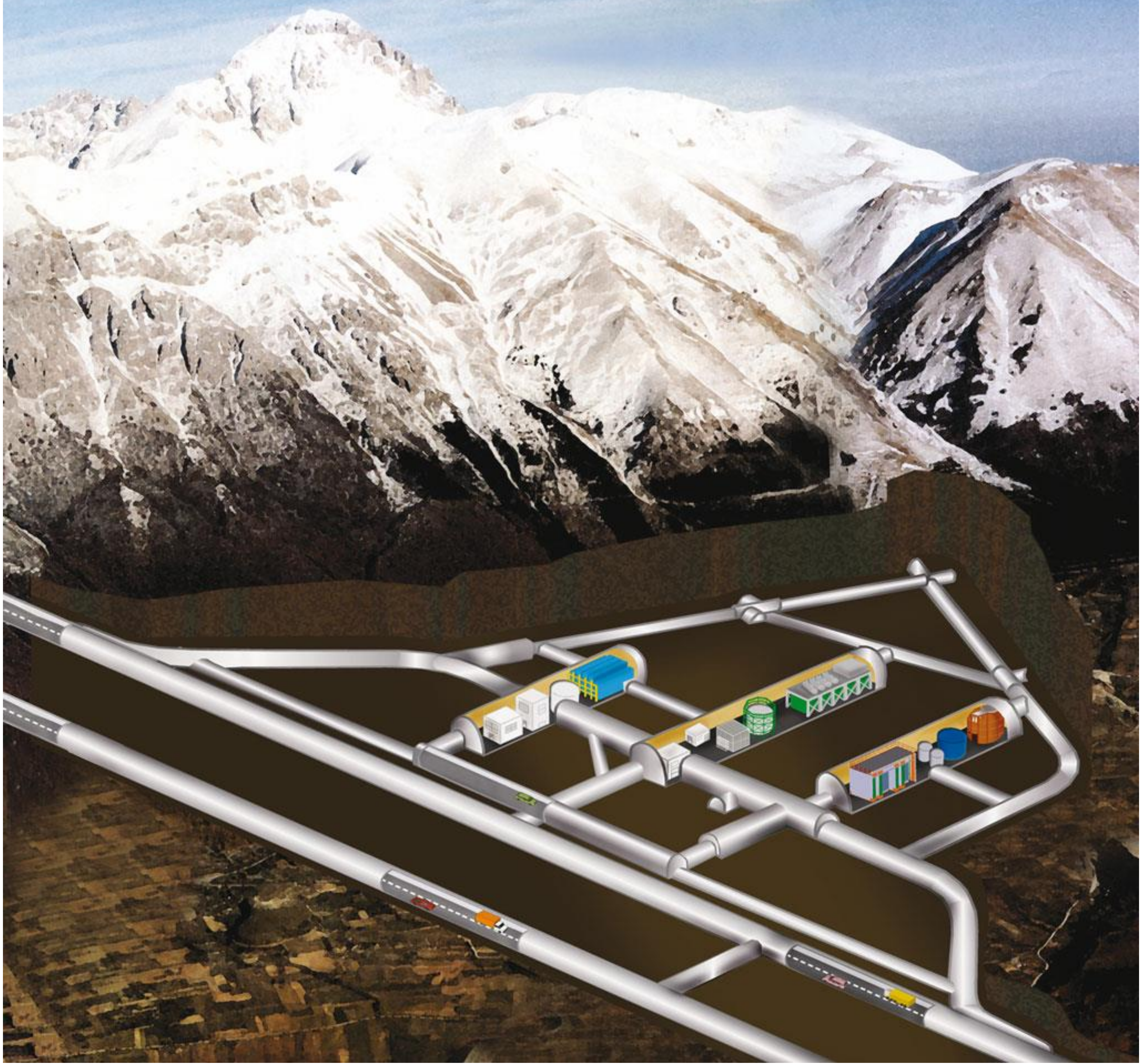
Energy 8.04 keV



2p –>1s transition violating Pauli principle

Energy 7.7 keV

Messiah Greenberg superselection rule



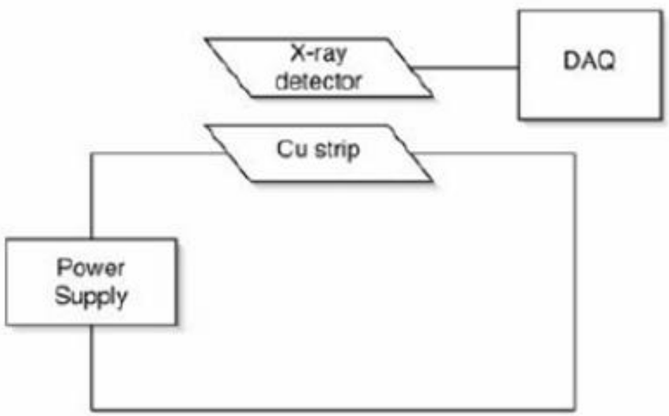
Greenberg, O. W. & Mohapatra, R. N., Phys Rev Lett 59, (1987).
E. Ramberg and G. A. Snow, Phys Lett B 238, 438–441(1990)

Search for anomalous electronic transitions in Cu induced by a circulating current

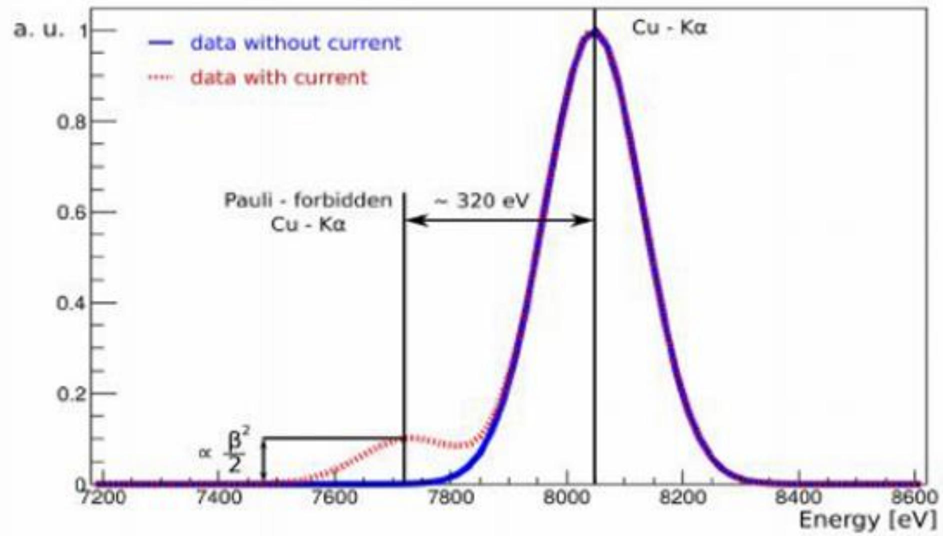
introduced electrons interact with the valence electrons

search transition from 2p to 1s already filled by 2 electrons

alternated to X-ray background measurements without current



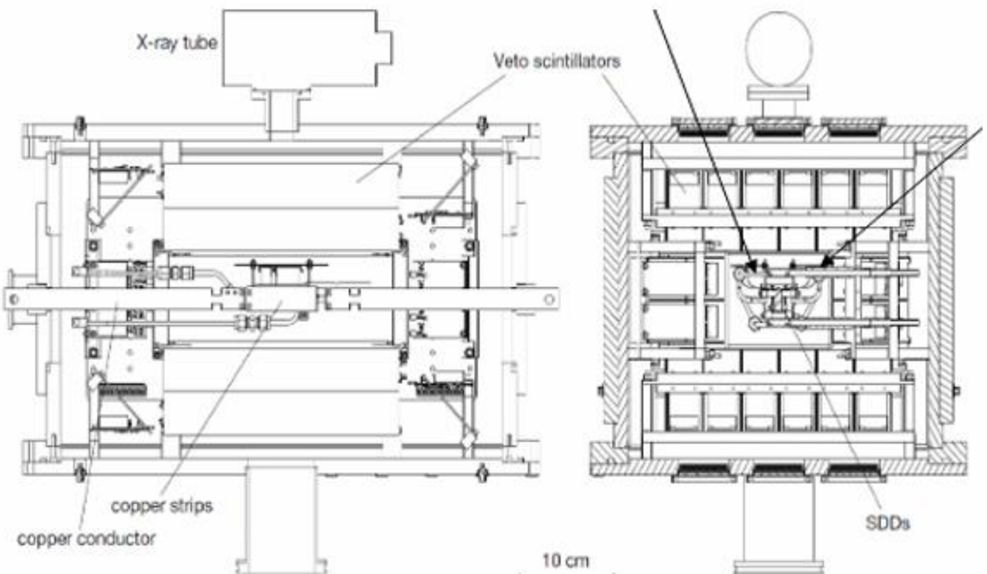
PEP Violation Signal:

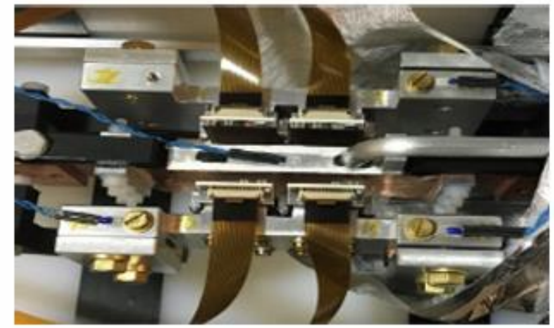


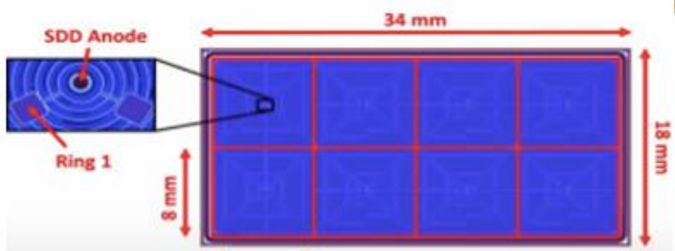

Nat. Phys. (2020)

The VIP-2 Experiment

*Silicon Drift Detectors (**SDDs**) higher resolution (190 eV FWHM at 8.0 →keV), faster (triggerable) detectors. 4 arrays of 2 x 4 SDDs 8mm x 8mm each, liquid argon closed circuit cooling 170 °C*







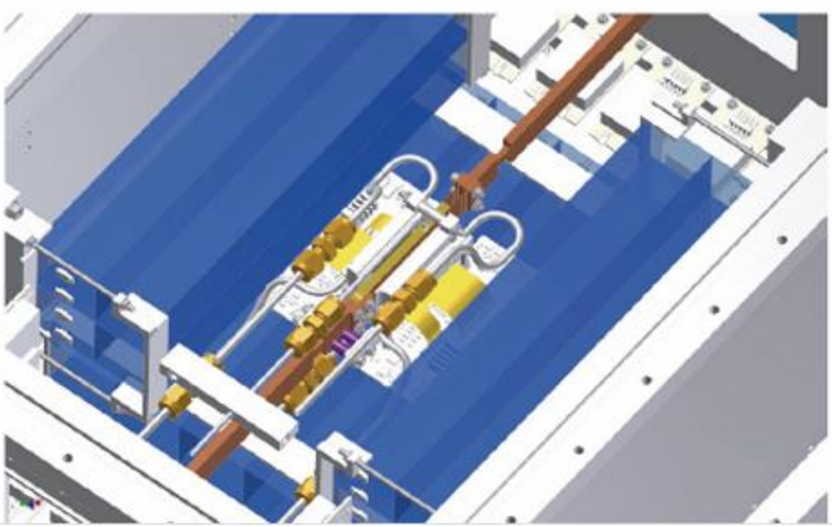
The VIP-2 Experiment

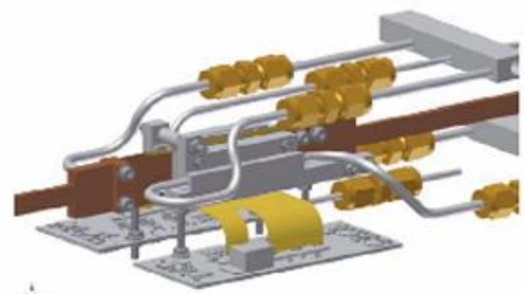
2 strip shaped Cu targets (25 um x 7 cm x 2 cm) more compact target → higher acceptance, thinner → ***higher efficiency***
DC current supply to Cu bars

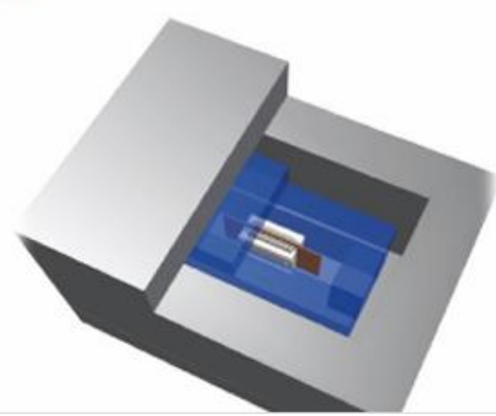
*Cu strips cooled by a closed Fryka chiller circuit →**higher current***

(100 A) @ 20 °C of Cu target implies 1 °K heating in SDDs

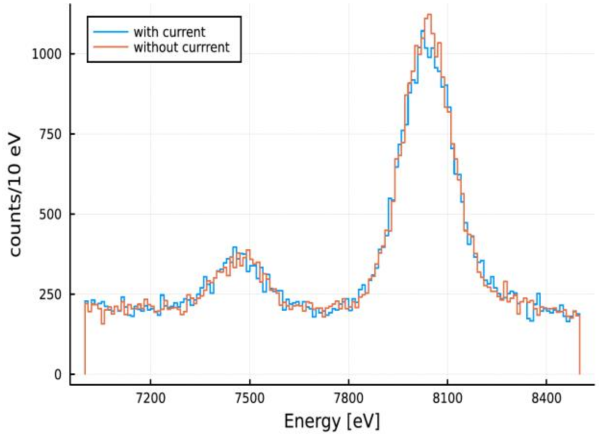
Sketch of the VIP2 Setup:







Symmetry 2022, *14*(5), 893; https://doi.org/10.3390/sym1405089



VIP-2 calibrated data in the region-of-interest 7000-8500 eV, of about two years of data taking (May 2019 to May 2021). The spectrum of the data acquired with a current circulating in the target is shown in blue. Data taken without current in the target, used as reference and control, shown in red. The copper and nickel K_α lines are visible in the spectra.

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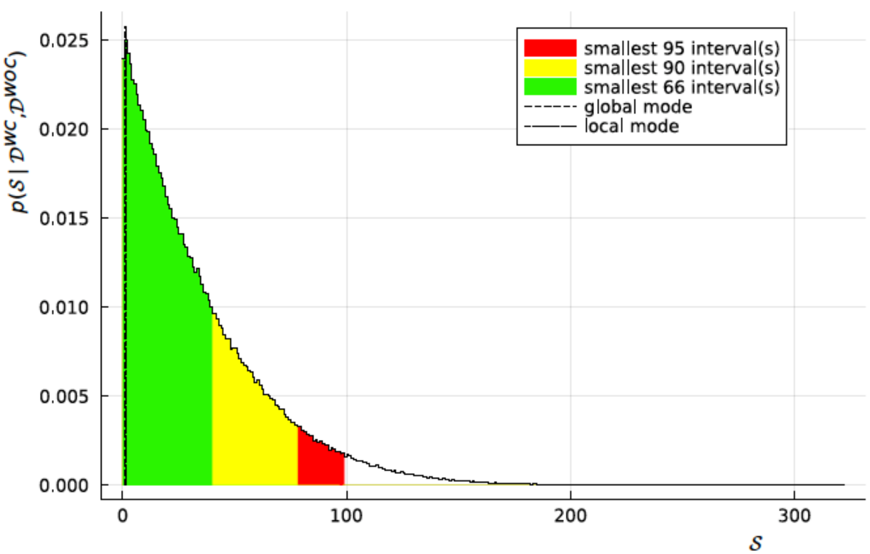
Testing the Pauli Exclusion Principle with the VIP-2 Experiment

by Fabrizio Napolitano [1,*], Sergio Bartalucci [1], Sergio Bertolucci [2], Massimiliano Bazzi [1], Mario Bragadireanu [1,3], Cesidio Capoccia [1], Michael Cargnelli [4], Alberto Clozza [1], Luca De Paolis [1], Raffaele Del Grande [1,5,6], Carlo Fiorini [7], Carlo Guaraldo [1], Mihail Iliescu [1], Matthias Laubenstein [8], Johann Marton [1,4], Marco Miliucci [1], Edoardo Milotti [9], Federico Nola [10], Kristian Piscicchia [1,5], Alessio Porcelli [1,4], + Show full author list

Bayesian analysis **result:** stromgest limits on PEPV probablity for electrons:



$$\beta^2/2 < 6.8 \cdot 10^{-43}$$

PEP violation in quantum gravity

Quantum gravity models can embed PEP violating transitions

PEP is a consequence of the spin statistics theorem based on: Lorentz/Poincaré and CPT symmetries; locality; unitarity and causality. Deeply related to the very same nature of space and time

↓

Non-commutativity of space-time is common to several quantum gravity frameworks (e.g. *k*-Poincarè, θ-Poincarè)

↓

non-commutativity induces a deformation of the Lorentz symmetry and of the locality → naturally encodes the violation of PEP not constrained by MG

PEP violation is suppressed with δ^2 (E, Λ)
E is the characteristic transition energy, Λ is the scale of the space-time non-commutativity emergence.

A. P. Balachandran, G. Mangano, A. Pinzul and S. Vaidya, Int. J. Mod. Phys. A 21 (2006) 3111
A.P. Balachandran, T.R. Govindarajan, G. Mangano, A. Pinzul, B.A. Qureshi and S. Vaidya, Phys. Rev. D 75 (2007)
A. Addazi, P. Belli, R. Bernabei and A. Marciano, Chin. Phys. C 42 (2018) no.9

PHYSICAL REVIEW LETTERS **129,** 131301 (2022)

Strongest Atomic Physics Bounds on Noncommutative Quantum Gravity Models

Kristian Piscicchia,[2,3] Andrea Addazi,[1,3,*] Antonino Marcianò,[4,3,†] Massimiliano Bazzi,[3] Michael Cargnelli,[5,3] Alberto Clozza,[3] Luca De Paolis,[3] Raffaele Del Grande,[6,3] Carlo Guaraldo,[3] Mihail Antoniu Iliescu,[3] Matthias Laubenstein,[7] Johann Marton,[5,3] Marco Miliucci,[3] Fabrizio Napolitano,[3] Alessio Porcelli,[5,3] Alessandro Scordo,[3] Diana Laura Sirghi,[3,8] Florin Sirghi,[3,8] Oton Vazquez Doce,[3] Johann Zmeskal,[5,3] and Catalina Curceanu[3,8]

The analysis yields stringent bounds on the noncommutativity energy scale, which exclude θ-Poincaré up to 2.6×10^2 Planck scales when the "electriclike" components of the $\theta_{\mu\nu}$ tensor are different from zero, and up to 6.9×10^{-2} Planck scales if they vanish, thus providing the strongest (atomic-transitions) experimental test of the model.

Accepted Paper

Experimental test of noncommutative quantum gravity by VIP-2 Lead

Phys. Rev. D

Kristian Piscicchia, Andrea Addazi, Antonino Marcianò, Massimiliano Bazzi, Michael Cargnelli, Alberto Clozza, Luca De Paolis, Raffaele Del Grande, Carlo Guaraldo, Mihail Antoniu Iliescu, Matthias Laubenstein, Johann Marton, Marco Miliucci, Fabrizio Napolitano, Alessio Porcelli, Alessandro Scordo, Diana Laura Sirghi, Florin Sirghi, Oton Vazquez Doce, Johann Zmeskal, and Catalina Curceanu

Accepted 7 December 2022

We can gain a lot on NUCLEAR PEP violation

First Experimental Survey of a Whole Class of Non-Commutative Quantum Gravity Models in the VIP-2 Lead Underground Experiment, *Universe 2023, 9, 32*

$$\delta^2 = c_k \left(\frac{E}{\Lambda'_k} \right)^k = \left(\frac{E}{\Lambda_k} \right)^k ,$$

The case k = 3, introduces a deformation of the space-time and momentum algebra that is appropriate for the "triply special relativity" model and involves a third invariant scale (other than the velocity of light and the Planck energy), associated to the cosmological constant by the authors.

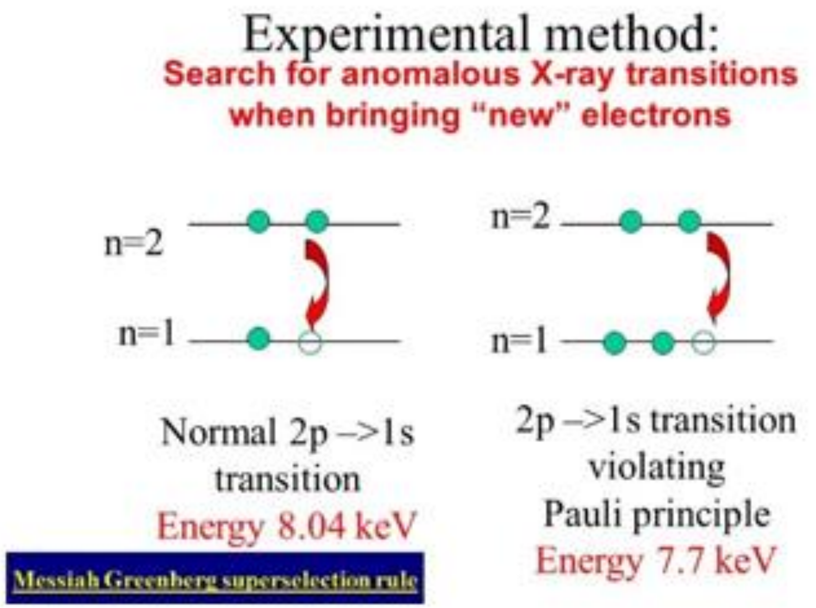
As a consequence, the measurement is very sensitive to high orders in the power series expansion of the Pauli violation probability, which allows to set the first constraint to the "triply special relativity" model proposed by Kowalski-Glikman and Smolin.
The characteristic energy scale of the model is bound to Λ > 5.6 · 10−9 Planck scales**

Future plans: test other QG models – with directionality (magnetic field) –
What about tests on nucleons? Higher E

New experiment at SPES:

Search for anomalous transitions when bringing "new" protons

First such measurement: Miljanić, Đ., et al. "Test of the Pauli principle in nuclear reactions." Physics Letters B 252.3 (1990): 487-490 at Legnaro!



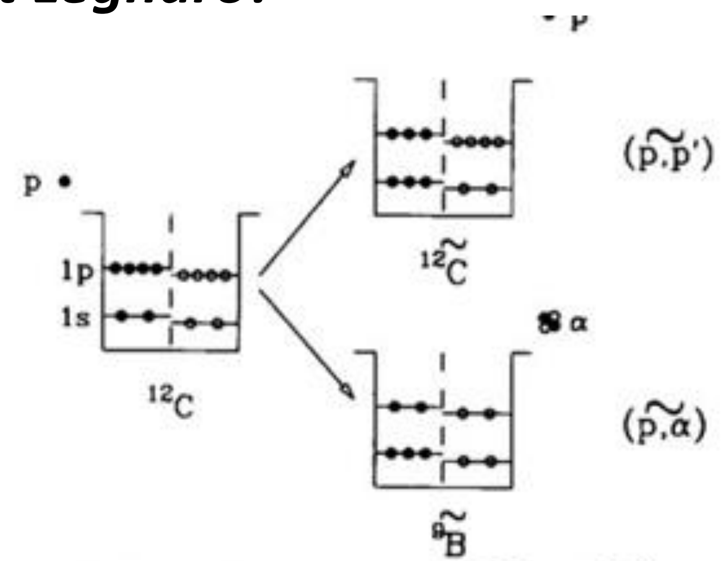


Fig. 1. The PEP violating processes: the $(\widetilde{p,p'})$ and $(\widetilde{p,\alpha})$ reactions.

Experimental Concept (Miljanić et al., 1990)

- Study (p, p′) and (p, α) reactions on carbon nuclei
- Hypothesis: A proton could end into a fully occupied nuclear shell (PEP violation)
- Expected signature: high-energy protons and α-particles (and gammas!)
- Analogy: Like forbidden atomic transitions emitting X-rays, but in nuclei

Experimental Setup

- Beam: 3 MeV protons from CN Van de Graaff (LNL)
- Target: Carbon foil (9 mg/cm^2)
- Detection: Silicon detector telescopes for protons and α-particles
- Energy vs energy-loss (ΔE–E) analysis
- Calibration: ^{3}He + ^{9}Be and other light-nuclei reactions

Results & Limits

- No high-energy protons (5–28 MeV) or α-particles (14–27 MeV) observed
- Upper limits on differential cross sections:
  (p, p′): < 40 fb/sr
  (p, α): < 56 fb/sr

- Cross-section PEP violating transition ratios (vs elastic scattering):
  (p, p′): $< 1.3 \times 10^{-13}$
  (p, α): $< 1.8 \times 10^{-13}$

Significance & Future Outlook

- First direct test of PEP in nuclear reactions
- Results set limits on PEP violations in nucleons
- Can be much improved with:
  Higher beam currents
  Longer measurement times
  Better detection system
  …………………….
- Forms foundation for future experiments at SPES and beyond

PEP-Violation Detection Setup starting ideas

Proton beam hits a 40 μm thick ^{12}C target (9 mg/cm^2) in a scattering chamber

Search for PEP-violating (p, p′) inelastic scattering: **PEP-violating signal = higher energy than elastic scattering (to be investigated)**

→ Signature: high-energy outgoing proton and **anomalous gamma**

Detection via two plastic scintillators + photomultipliers + **HPGe**

Scintillators positioned at ~50° relative to beam axis

Proton energy measured using: Energy loss (dE/dx); Time-of-flight

→ Baseline for future spectroscopy and BSM channels (e.g., (p, γ)) – Ge detectors

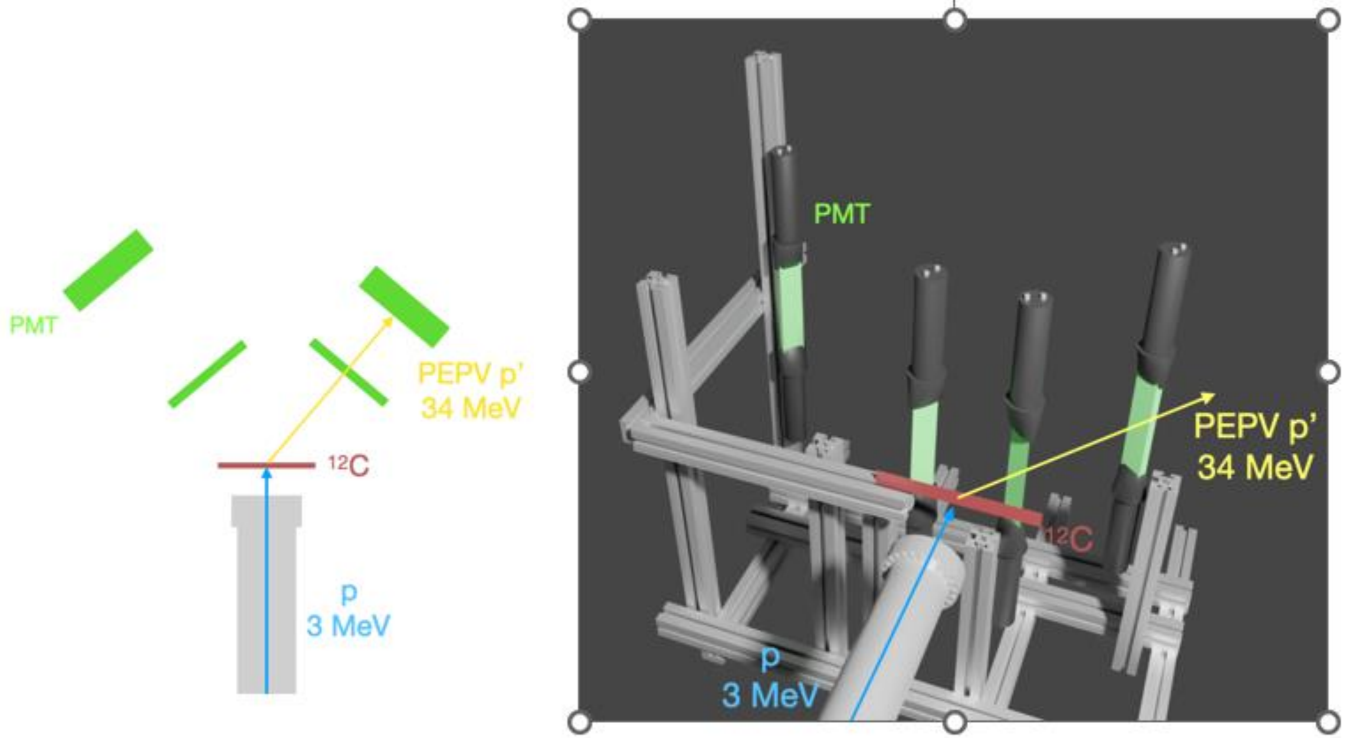


Figure 2: *Schematic view of the test setup, left, and the 3D render showing the support element, right.*

Energy Reconstruction Strategy

Two-stage scintillator detection:

Thin scintillator (<1 mm) for precise dE measurement (light yield)

Thick scintillator (~10 mm) to fully stop protons (up to 30-40 MeV) for total energy measurement

→ Crucial for detecting PEP-violating signals

Time-of-Flight (ToF) system also:

Arm length: 50 cm → ~6 ns for 30-40 MeV protons

Timing resolution: ~140 ps (SIDDHARTA-2 benchmark)

Second arm at shorter distance: higher acceptance, lower resolution (for systematics study)

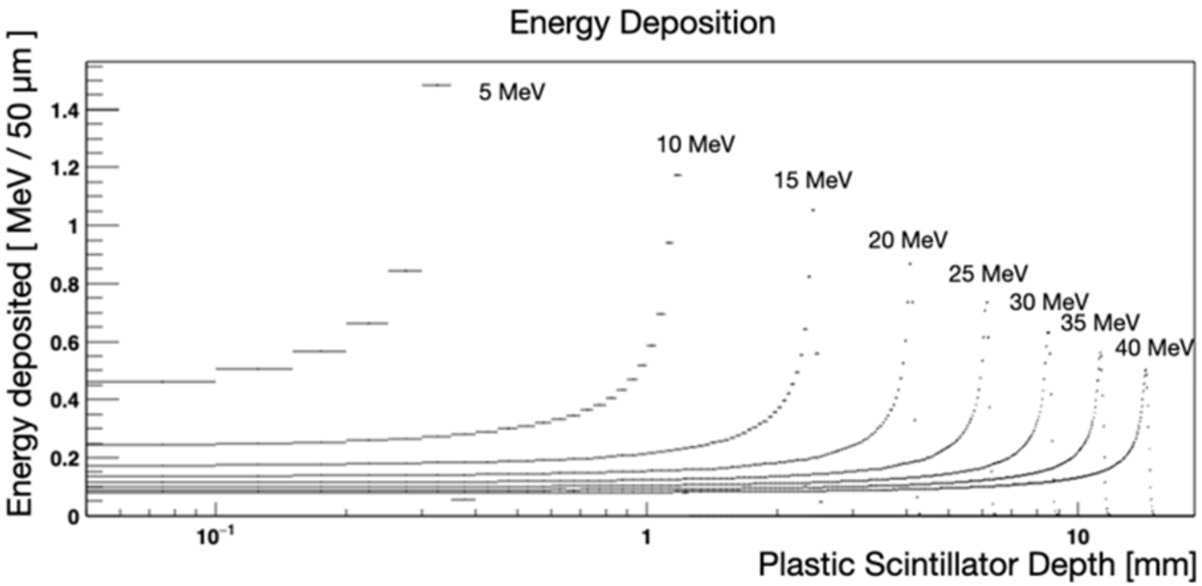


Figure 3: *Energy deposition in plastic scintillator as a function of the depth for different energies of an incoming proton.*

Experimental Setup & Feasibility – SPES Cyclotron

Beam & Motivation

Use of high-intensity proton beam from SPES Cyclotron; select energy

Aim: Search for (p, p′) non-Paulian nuclear transitions

→ Building on 1990s pioneering work at LNL but much advanced

Key Components

Target System: Thin ^{12}C foil (or similar), optimized for clean proton-induced reactions

Detection System: Plastic scintillator telescope + PMTs (High-precision energy and timing readout); **HPGe upgrades for enhanced performance: gamma spectroscopy**

Background Suppression

Passive + active shielding

Time-of-flight (ToF) to discriminate elastic events

Beam Monitoring

Real-time proton flux and energy control

Ensures high reproducibility and systematic reliability

To do

Nuclear physics calculations (including energies PEP violating transitions)

Monte Carlo detailed simulations

Setup design

Test setup

Expected Outcomes & Scientific Impact

Set new strongest upper limits on Pauli Exclusion Principle (PEP) violation for protons (MG superselection rule)

If PEP violation is observed:

→ Groundbreaking evidence for ***new physics beyond the Standard Model***

Impact in: Quantum gravity; Extra dimensions; Fundamental symmetry violations…….

Broader contributions:

Methodological advances in high-precision nuclear spectroscopy

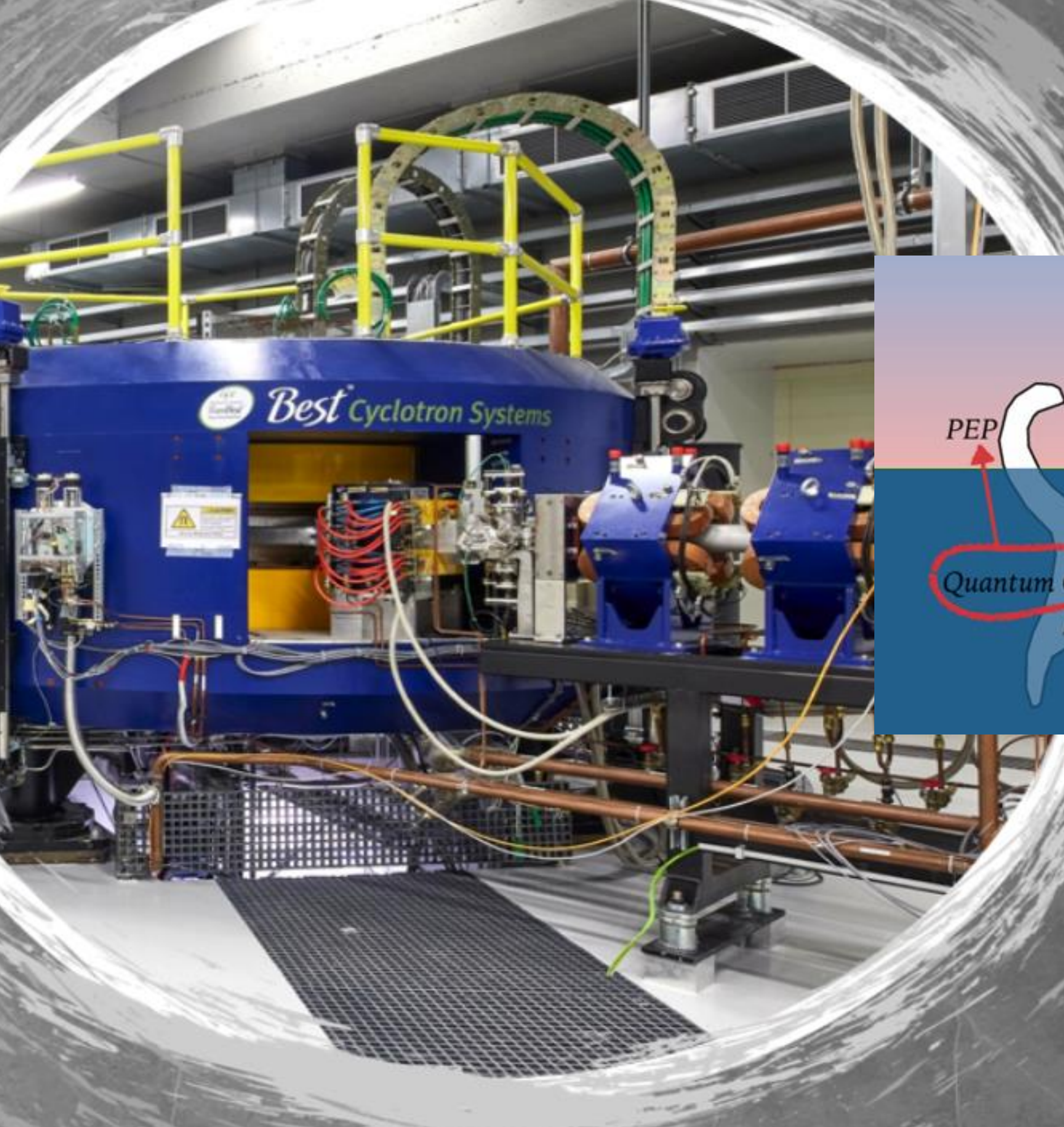
Relevance to nuclear structure studies and astrophysical modeling

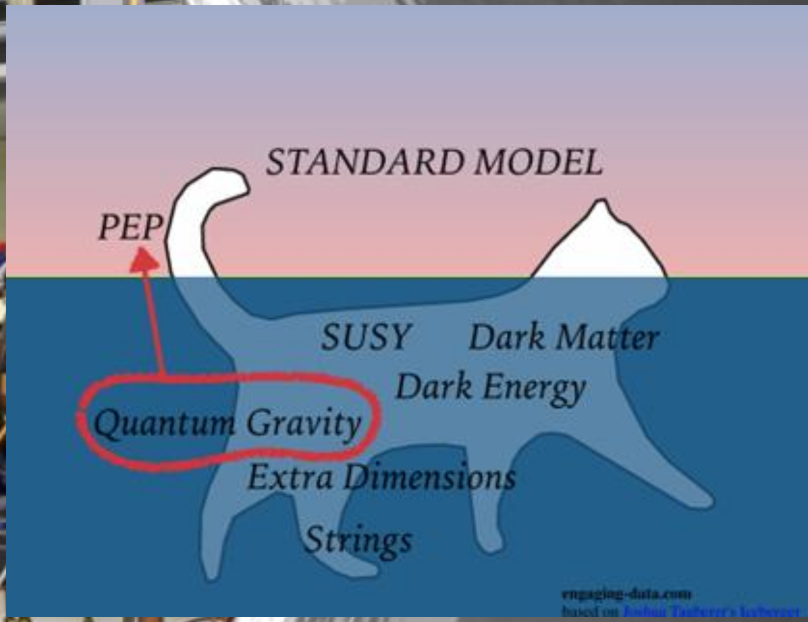
Conclusion & Outlook

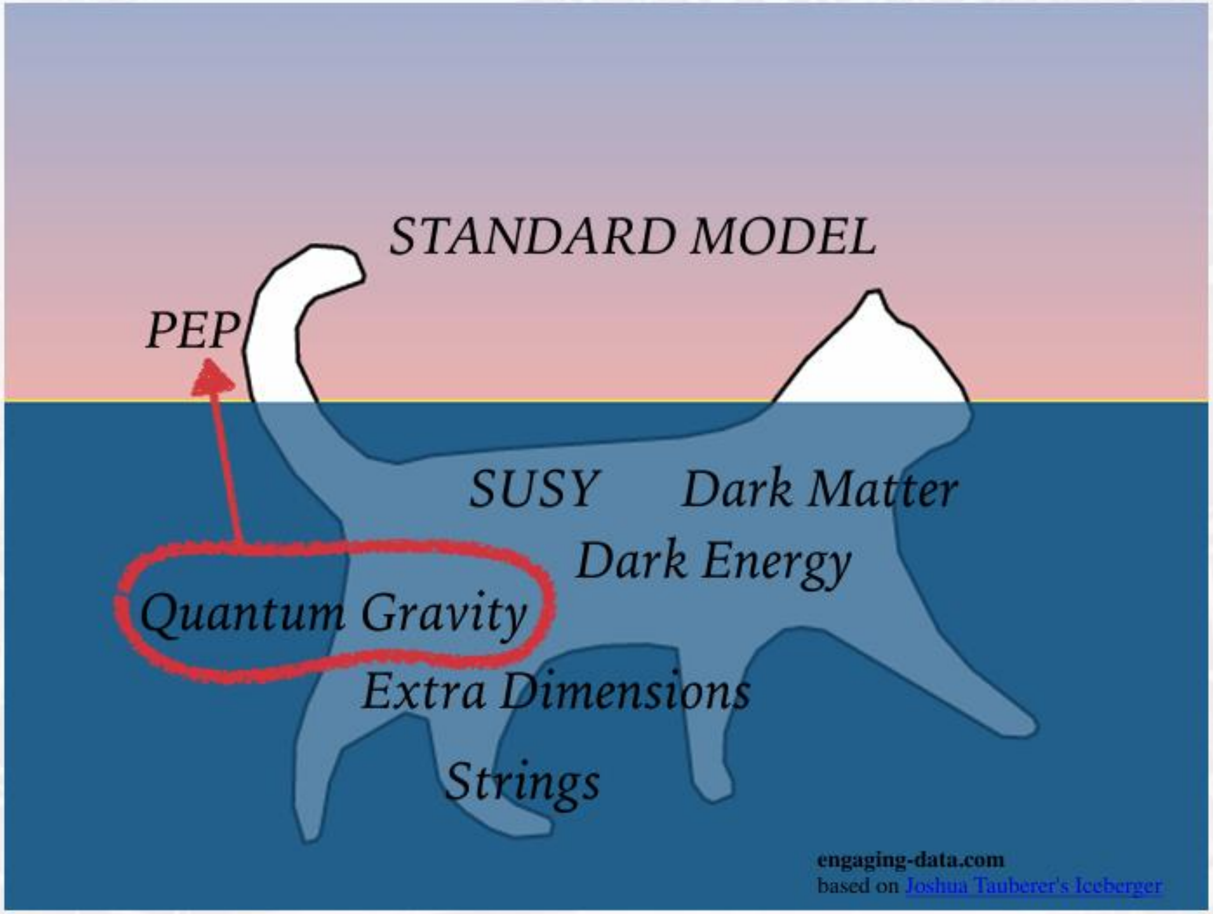
Strong interest in conducting this novel experiment at the SPES Cyclotron

Committed to collaborative refinement of the approach within the nuclear physics community

Goal: Maximize scientific return and enable high-impact publication


Best Cyclotron Systems


STANDARD MODEL
PEP
SUSY
Dark Matter
Dark Energy
Quantum Gravity
Extra Dimensions
Strings
engaging-data.com



BSM theories embedding extra dimensions, non commutative and/or discrete spacetime could have effect on PEP

At the root of the Exclusion Principle: proof of spin-statistics theorem by Lüders and Zumino

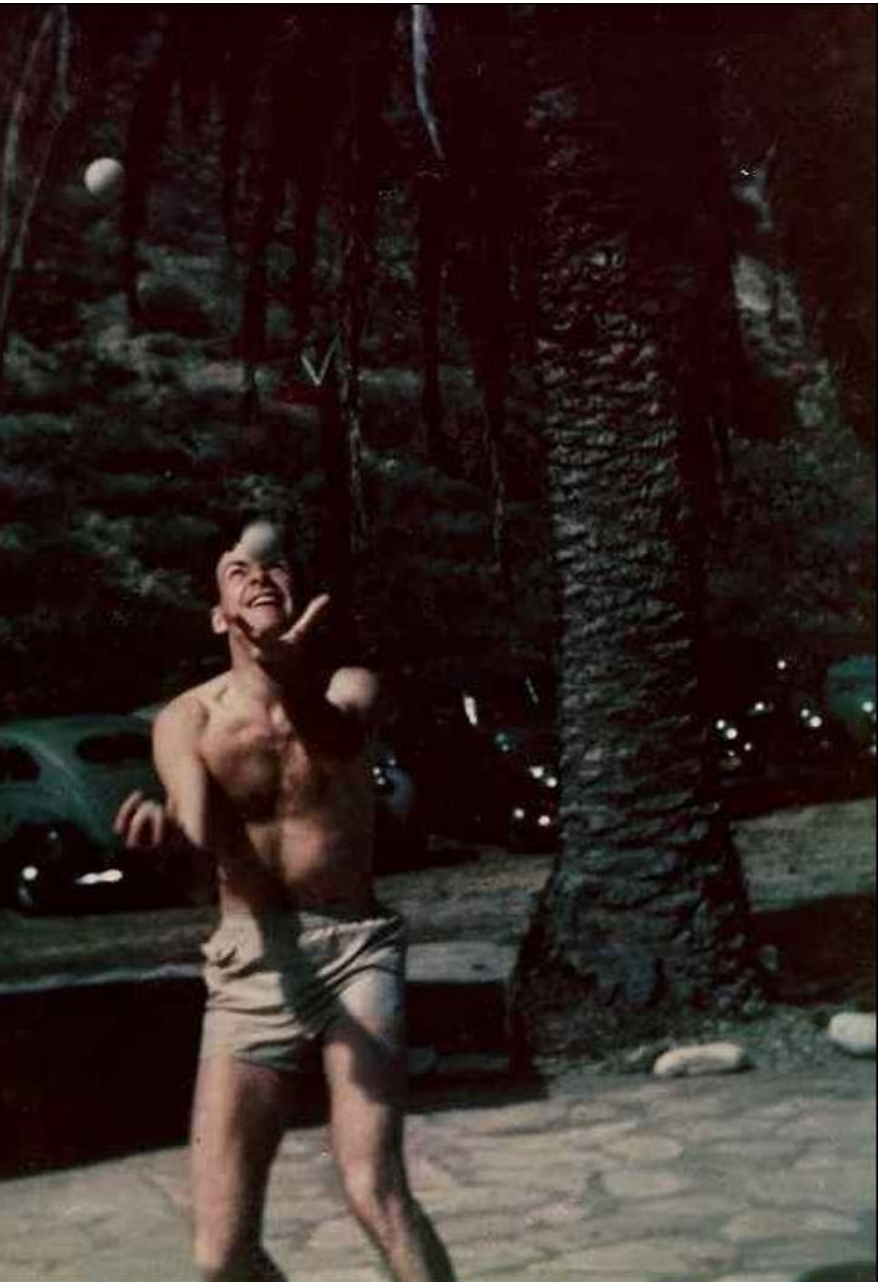
Postulates:

I. **The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)**
II. **Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality - microcausality)**
III. **The vacuum is the state of lowest energy**
IV. **The metric of the Hilbert space is positive definite**
V. **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)

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