SIF 2024 - Sep 9 – 13, 2024, Bologna

Testing the Pauli Exclusion Principle across the periodic table with the VIP-3 experiment

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on behalf of the **VIP collaboration**

Outline

1. **Testing Pauli Esclusion Principle with VIP experiment**

2. **VIP-3 setup for testing PEP in Zr, Pd, Ag and Sn**

3. **Predicting violations of PEP with MultiConfiguration Dirac-Fock Calculations**

Testing the Pauli Exclusion Principle (PEP)

The PEP states that two identical fermions cannot occupy the same quantum state in a system.

Why testing PEP?

1. **Foundation of Quantum Mechanics**: Testing PEP confirms the stability of matter and the core principles of quantum theory.

2. **Potential for New Physics**: Any PEP violation could lead to groundbreaking discoveries beyond the Standard Model.

3. **Refinement of Scientific Knowledge**: It enhances confidence in existing theories and improves precision in experimental techniques.

Violating the PEP with the β parameter

Possible violations, with two fermions occupying the same state, are included with a probability amplitude β:

$$a^\dagger|0\rangle = |1\rangle \quad a^\dagger|1\rangle = \beta|2\rangle \quad a^\dagger|2\rangle = 0$$
$$a|0\rangle = 0 \quad a|1\rangle = |0\rangle \quad a|2\rangle = \beta|1\rangle$$

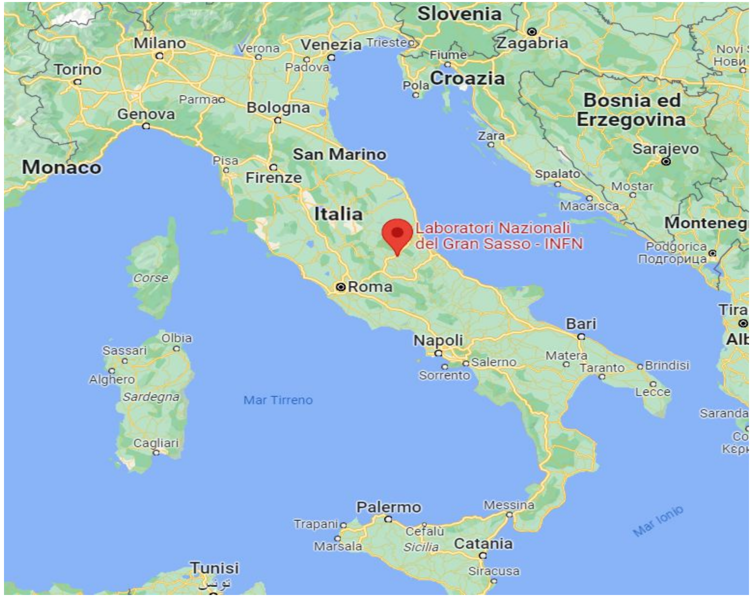
Models of PEP violation:

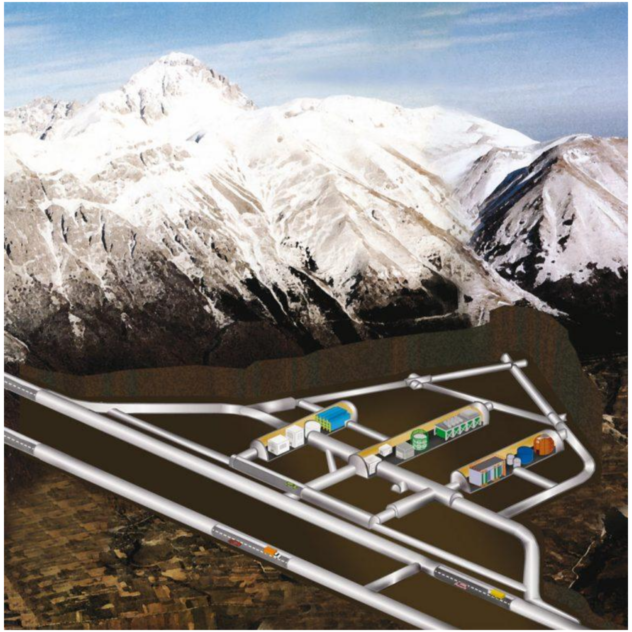
- Pioneering work of **Fermi, Gentile, Green**
- **Igniatiev and Kuzmin [**A.Y. Ignatiev, V.A. Kuzmin, Proceedings of the Seminar, Tbilisi, USSR, 15-17 April 1986] (deformation of the standard Fermi oscillator)
- **Rahal and Campa** [V. Rahal, A. Campa, Thermodynamic implications of a violation of the Pauli principle. Phys. Rev. A 38(7), 3728–3731 (1988)]

Experiments on PEP violation:

- **Ramberg and Snow (1988):** $\beta^2/2 \leq 10^{-26}$ (lepton-lepton case)
- **DAMA (2009):** $\beta^2/2 \leq 10^{-47}$ (hadron-lepton case)
- **Borexino (2011):** $\beta^2/2 \leq 10^{-60}$ (hadron-hadron case)

Testing Quantum Mechanics at the Gran Sasso National Laboratory (LNGS)

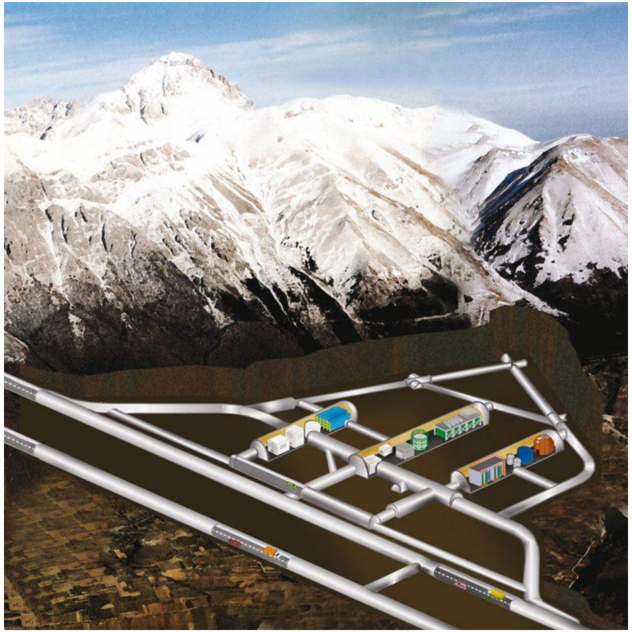




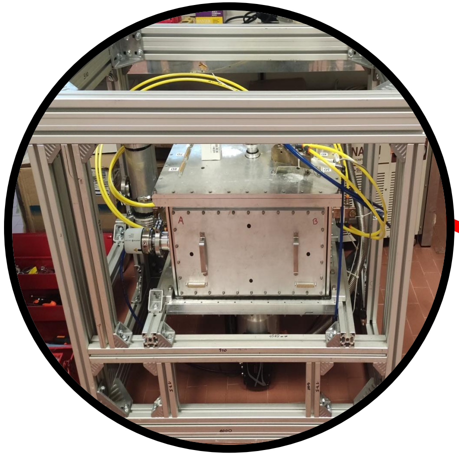
Testing Quantum Mechanics at the Gran Sasso National Laboratory (LNGS)

The experiments are performed in the low-background environment of the underground Gran Sasso National Laboratory of INFN:

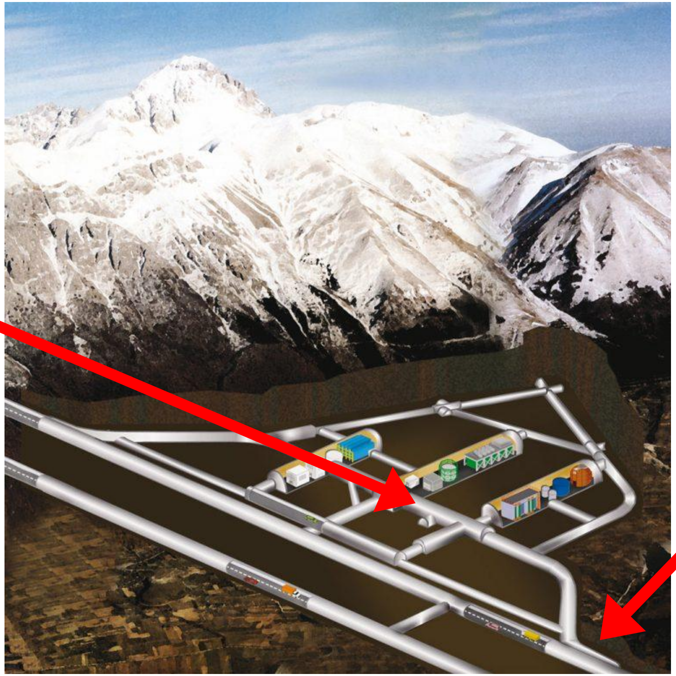
- Overburden corresponding to a minimum thickness of 3600 m of water equivalent
- The muon flux is reduced by almost six orders of magnitude
- The main background source consists of γ-radiation produced by long-lived γ-emitting primordial isotopes and their decay products



The LNGS laboratories environment



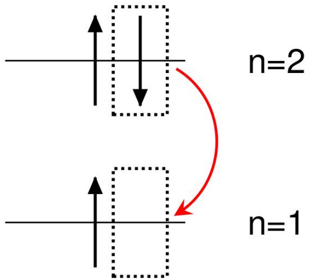
VIP-2 Setup



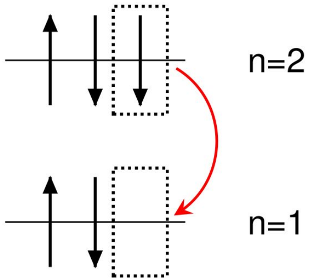
LNGS

Measuring $\beta^2/2$ with VIP (VIolation of Pauli Exclusion Principle) experiment in Atomic Transitions

Searching violating transitions through the Kα (2p->1s) X-rays emission line in Copper



Normal Kα line
$E(CuK_\alpha) = 8041$ eV



Violating Kα line
$E(CuK_\alpha) = 7729$ eV

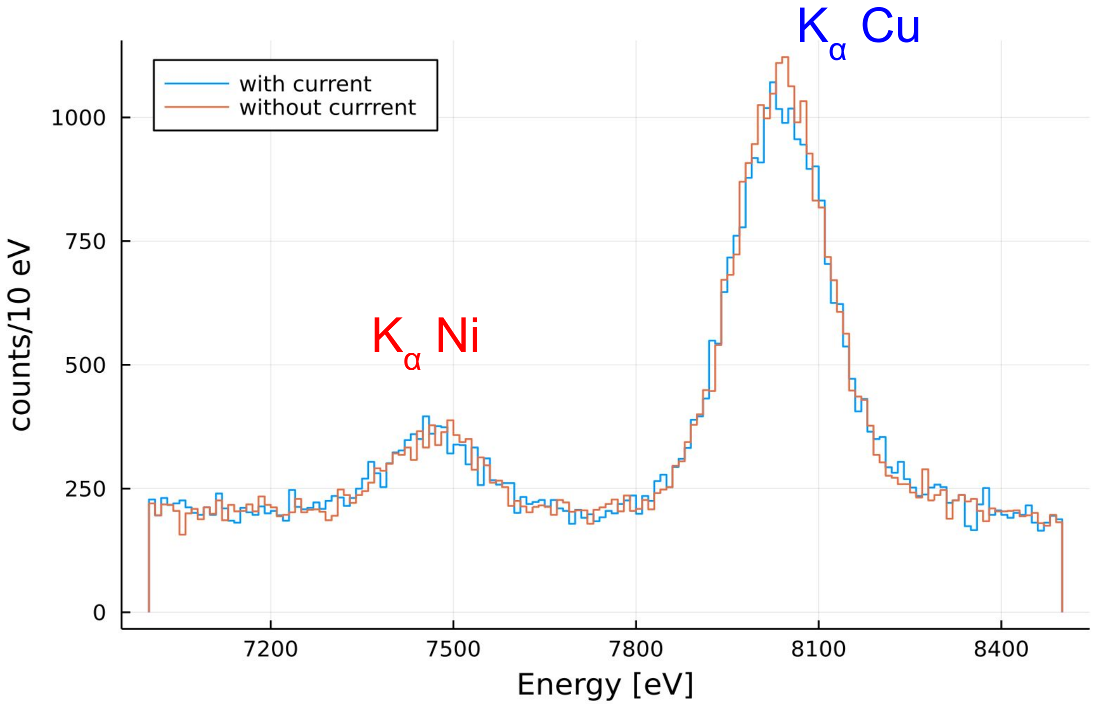
Open systems:
(testing newly injected electrons)

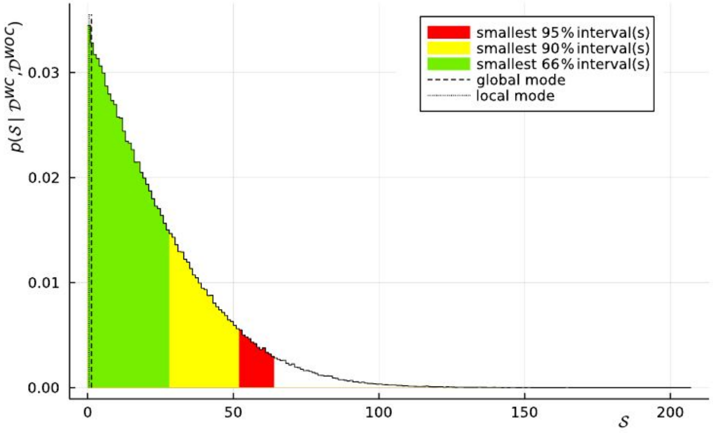
- **VIP**: $\beta^2/2 \leq 4.7 \cdot 10^{-26}$
- **VIP-2**: $\beta^2/2 \leq 8.6 \cdot 10^{-31}$
- **VIP-3**: (future)

Close system:
(testing spontaneous emissions)

- **VIP-lead**
- **BEGe**

Extracting β²/2 from the X-rays emission spectrum



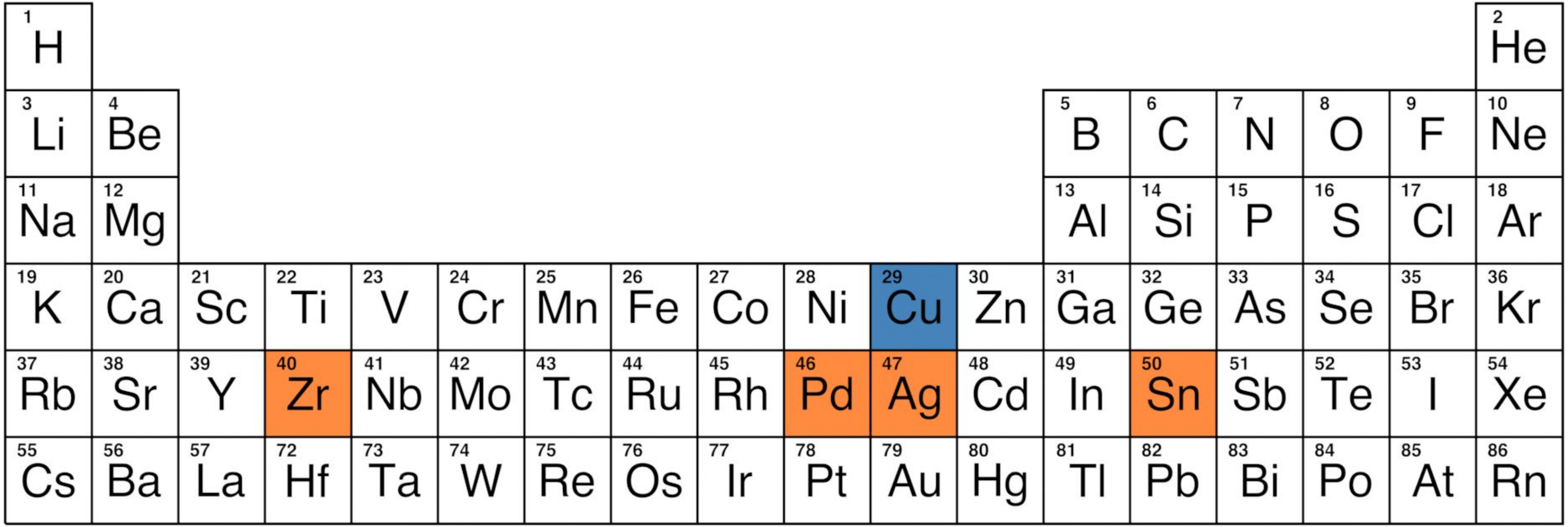


$$S \simeq \frac{\beta^2}{2} N_{new} \frac{N_{int}}{10} \cdot 7.25x10^{-2}$$

- N_{new} number of newly injected electrons equals to IΔt/e
- N_{int} / 10 number of interactions
- 7.25 x 10^{-2} simulated efficiency

Napolitano, F., Bartalucci, S., Bertolucci, S., Bazzi, M., Bragadireanu, M., Capoccia, C., ... & Curceanu, C. (2022). Testing the Pauli exclusion principle with the VIP-2 experiment. Symmetry, 14(5), 893.

Testing PEP across the periodic table with VIP-3



Testing PEP across the periodic table with VIP-3

Searching PEP violating atomic transitions from **VIP-2** (Cu) to multiple elements with **VIP-3** (Zr,Pd,Ag,Sn)

- *"The special place enjoyed by the Pauli principle in modern theoretical physics does not mean that this principle does not require further and exhaustive experimental tests. On the contrary, it is specifically the fundamental nature of the Pauli principle which would make such tests, over the entire periodic table, of special interest"*

  Okun L. Possible violation of the Pauli principle in atoms. JETP Lett. 1987, 46, 529532

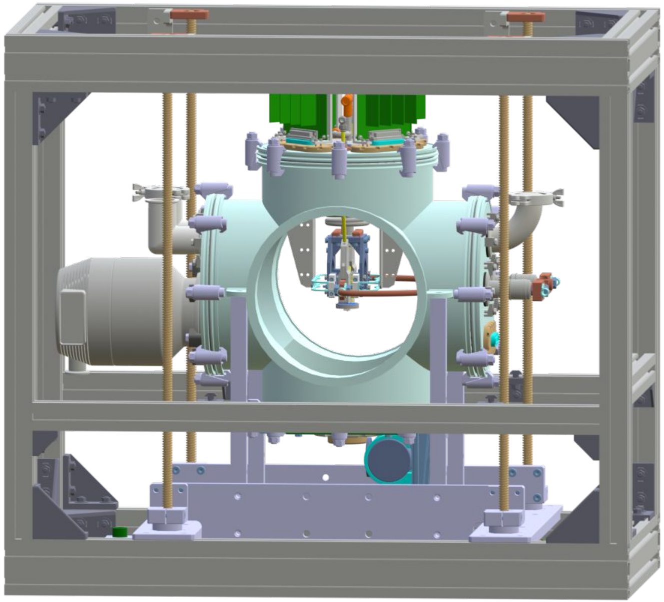
- **Dependence on Z** vastly discussed in our recent papers e.g. Universe 2023, 9(7), 321

- Different atomic environments (**Higher Atomic Numbers**) could reveal subtle effects.

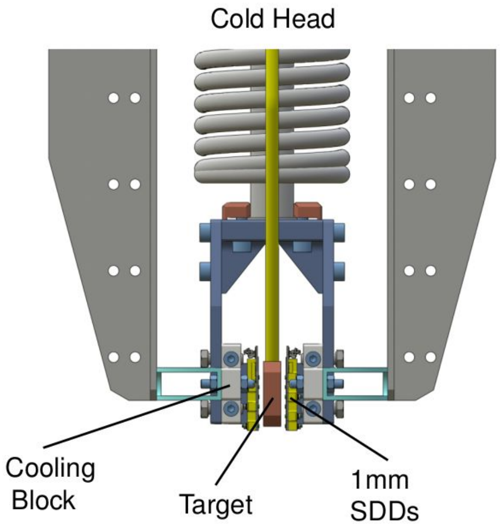
- **Comprehensive testing** ensures no violation under various conditions.

Manti, S., Bazzi, M., Bortolotti, N., Capoccia, C., Cargnelli, M., Clozza, A., ... & Curceanu, C. (2024). Testing the Pauli Exclusion Principle across the Periodic Table with the VIP-3 Experiment. *Entropy*, *26*(9), 752.

VIP-3 experimental setup for different targets elements



- **Vacuum** 10^{-5} mbar
- **Temperature** -140 ℃
- **Current** 400 A



Targets in Zr, Pd, Ag and Sn:

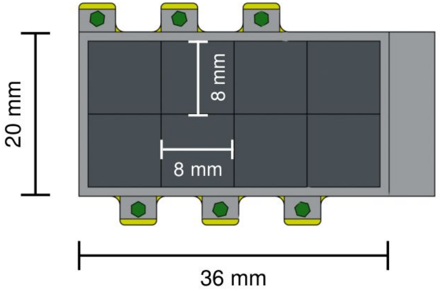
- $E(ZrK_{\alpha})$ = 17.7 keV
- $E(PdK_{\alpha})$ = 21.1 keV
- $E(AgK_{\alpha})$ = 22.1 keV
- $E(SnK_{\alpha})$ = 25.2 keV

Energy calibration utilizing an internal Fe-55 source in conjunction with an X-ray tube

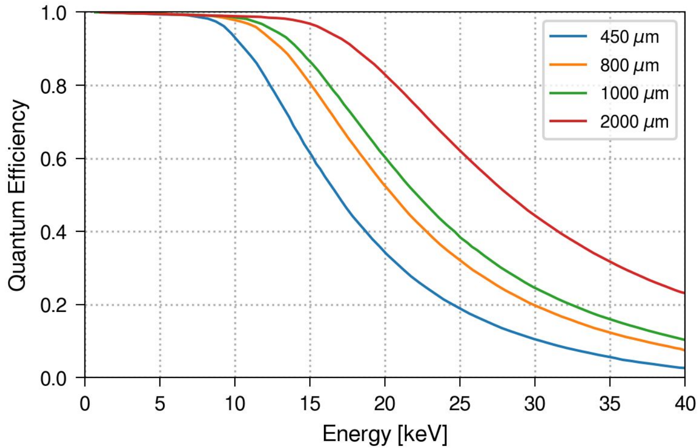
Heavier targets require an increased sensitivity

Effort to improve Silicon Drift Detectors (SDDs) developed in collaboration with **Politecnico di Milano** (PoliMi, Milan, Italy) and the **Fondazione Bruno Kessler** (FBK, Trento, Italy):

- **Thicker 1 mm SDDs** with improved efficiency
- Larger SDD unit consists of a **4 × 2 matrix**
- Energetic resolution of **137.5 eV FWHM at 5.9 keV**



Guard rings to reduce the charge-sharing effect at the edge of each unit



Toscano, L. G., Deda, G., Borghi, G., Carminati, M., Samusenko, A., Vignali, M. C., ... & Fiorini, C. (2024). Development of high-efficiency X-ray detectors based on 1 mm thick monolithic SDD arrays. Journal of Instrumentation, 19(07), P07039.

Predicting violating transition with a MCDF code

Calculations performed using the **MultiConfiguration Dirac-Fock** (MCDF) developed by **Desclaux** and **Indelicato** since the 1980s:

- Solve the MultiConfiguration Dirac-Fock equations (with all orbitals relaxed) including **various contributions self-consistently** (Coulomb, Breit, vacuum polarization).
- Include, besides **electrons**, several **exotic particles**, including bosons
- **Total Energy** of a given state either at the single configuration or multiconfiguration level
- Calculates **Radiative transition** probabilities **Auger transition** probabilities

$$\Psi = \sum_{v=1}^{NCF} W_v \phi^v(1, 2, \ldots, N; J, J_z) \qquad \mathrm{E_{tot}} = \sum_{\nu\mu} W_\nu W_\mu \langle \phi^\nu | H | \phi^\mu \rangle / \sum_\nu W_\nu^2 \qquad H = \sum_i H_D(i) + \sum_{ij} \left[\frac{1}{r_{ij}} + H_B(i, j) \right]$$

Predicting violating transition with a MCDF code

- **Pauli Violation Electron** is not antisymmetrized with respect to the total wavefunction
- Transition energy is reduced due to extra **electron screening**, resembling a Z-1 atom transition
- **Oxidation states** compatible with the closest full shell to avoid convergence issues with open shells configurations
- Predicted **violating shifts** to guide experiment and data analysis

Element	Configuration	$K\alpha_1$ [eV]	$K\alpha_1$ Shift [eV]	$K\alpha_2$ [eV]	$K\alpha_2$ Shift [eV]
Cu^{+1}	$[Ar]3d^{10}$	7749.3	298.1	7730.2	297.1
Zr^{+4}	[Kr]	15,366.0	407.1	15,284.2	404.4
Pd^{0}	$[Kr]4d^{10}$	20,709.6	466.2	20,556.5	462.1
Ag^{+1}	$[Kr]4d^{10}$	21,686.0	475.5	21,517.5	471.2
Sn^{+2}	$[Kr]5s^2 4d^{10}$	24,766.2	503.8	24,543.9	498.5

Manti, S., Bazzi, M., Bortolotti, N., Capoccia, C., Cargnelli, M., Clozza, A., ... & Curceanu, C. (2024). Testing the Pauli Exclusion Principle across the Periodic Table with the VIP-3 Experiment. *Entropy*, *26*(9), 752.

Conclusion

1. **Testing Pauli Esclusion Principle with VIP experiment**

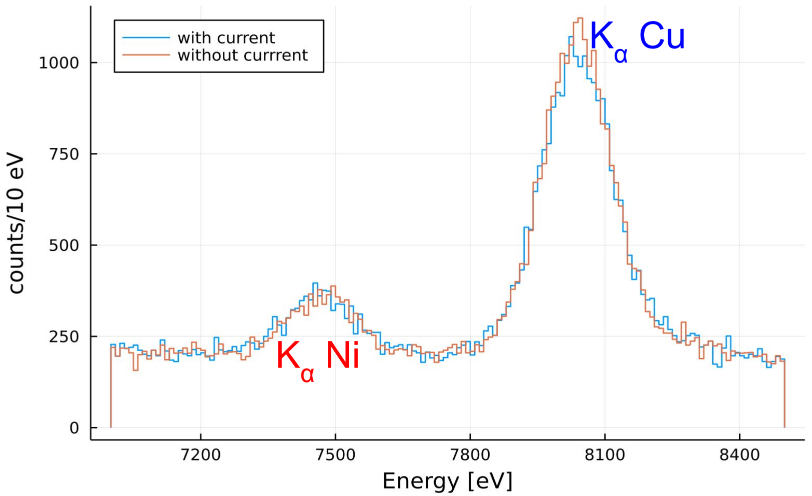
2. **VIP-3 setup for testing PEP for Zr, Pd, Ag and Sn**

3. **Predicting violations of PEP with MultiConfiguration Dirac-Fock Calculations**

Thank for your attention!

Spare

The value of $\beta^2/2$ is extracted from the amplitude S



$$S \simeq \frac{\beta^2}{2} N_{new} \frac{N_{int}}{10} \cdot 7.25x10^{-2} \Rightarrow \frac{\beta^2}{2} \simeq S \frac{N_{int}}{10} \frac{I\Delta t}{e} \cdot \frac{1}{7.25x10^{-2}}$$

- N_{new} number of newly injected electrons equals to $I\Delta t/e$
- N_{int} / 10 number of interactions
- 7.25×10^{-2} simulated efficiency

N_{int} estimated from:

- **Linear Scattering** $N_{int} = D / \mu \rightarrow \beta^2/2 = 10^{-31}$
- **Close Encounters** $N_{int} = T / t_E \rightarrow \beta^2/2 = 10^{-43}$