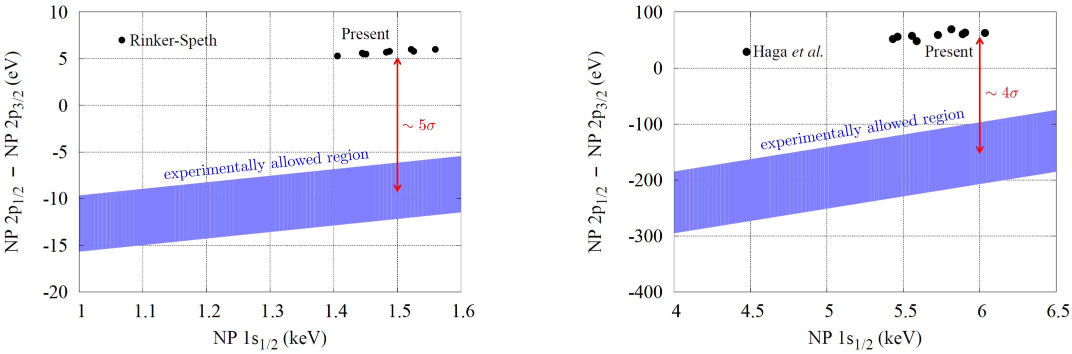
An update on the muonic fine-structure puzzle

Igor A. Valuev[a], Gianluca Colò[b,c], Xavier Roca-Maza[b,c], Konstantin Beyer[a], Matteo Tamburini[a],
Christoph H. Keitel[a], and Natalia S. Oreshkina[a]

[a] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[b] *Dipartimento di Fisica, Università degli Studi di Milano, via Celoria 16, I-20133 Milano, Italy*
[c] *INFN, Sezione di Milano, via Celoria 16, I-20133 Milano, Italy*

According to the principle of lepton universality, the only fundamental difference between the electron and the muon is their mass, namely $m_\mu \approx 207 m_e$. This simple fact has profound consequences for the so-called muonic atoms formed via capturing a muon by the nucleus of an ordinary atom. The muonic Bohr radius is 207 times smaller than the electronic one, which makes the muon an excellent probe to study essential nuclear properties. In practice, this is done by fitting theoretical muonic transition energies to measured ones while treating the nuclear property of interest as a free parameter. However, in a series of heavy muonic atoms such a procedure resulted in very poor fits (see, e.g., [1]), where the source of the discrepancies was narrowed down to the fine-structure splitting between the $2p_{1/2}$ and $2p_{3/2}$ energy levels. Remarkably, this muonic fine-structure puzzle has persisted for decades and stills remains unresolved to this day.

From the theoretical side, the most challenging and uncertain contribution to calculate is the nuclear polarization effect, which describes the dynamic interplay between atomic and internal nuclear degrees of freedom. For a long time, nuclear polarization has been naturally considered to be the main suspect responsible for the discrepancies. However, our recent study [2] provided strong evidence against this prevalent hypothesis (see Fig. 1). Furthermore, taking a closer look at the QED part of the calculations and improving the evaluation of the self-energy correction also did not alleviate the problem [3].



(a) (b)

Figure 1: Theoretical values of the nuclear-polarization corrections for μ-^{90}Zr (a) and μ-^{208}Pb (b) in relation to the experimentally allowed regions for $\left(|\Delta E^{\mathrm{NP}}_{2p_{1/2}}| - |\Delta E^{\mathrm{NP}}_{2p_{3/2}}|\right)$ and $|\Delta E^{\mathrm{NP}}_{1s_{1/2}}|$ [2].

An overview of the current status of the puzzle will be presented, and other potential solutions will be discussed, including some more exotic ideas such as contributions from new hypothetical interactions beyond the Standard Model.

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[1] P. Bergem, G. Piller, A. Rüetschi, L. A. Schaller, L. Schellenberg, and H. Schneuwly, Phys. Rev. C **37** (1998) 2821.

[2] I. A. Valuev, G. Colò, X. Roca-Maza, C. H. Keitel, and N. S. Oreshkina, Phys. Rev. Lett. **128** (2022) 203001.

[3] N. S. Oreshkina, Phys. Rev. Res. **4** (2022) L042040.