Letter of intent: **Mu4Rad - Muonic atoms for nuclear radii**

Randolf Pohl (JGU Mainz), Nancy Paul (LKB Paris), Ben Ohayon (Technion Haifa), Loredana Gastaldo (KIP, Heidelberg), Frederik Wauters (JGU Mainz)

1. Research objectives

The charge radius is a fundamental property of the nucleus, whose knowledge has implications in the development of nuclear structure theory, precision QED tests and searches for physics beyond the Standard model (BSM). Laser spectroscopy of muonic atoms has produced charge radii with unprecedented precision from the proton (Z=1) to the alpha particle (Z=2). For the proton charge radius, we have found a huge discrepancy to earlier proton radius measurements from hydrogen spectroscopy and elastic electron scattering, in particular from MAMI in Mainz. The origin of this discrepancy has not been understood, and measurements of other muonic radii is expected to help. Here, Z>=3 allows for relatively simple, solid targets for elastic electron scattering.
Beyond Z=2, laser spectroscopy of muonic ions is currently not possible. Instead, novel microcalorimeters have recently been developed by KIP, Heidelberg, which can be used to measure X-ray energies with unprecedented precision. These new devices allow for a ten-fold improvement of the charge radii for the lightest nuclei (up to $Z \approx 10$). As an example, Z=10 (Ne) is of great importance for BSM searches, because recent ultra-precise measurements of the bound-electron g-factor in Ne are strongly limited by the uncertainty in the charge radii of the Ne isotopes. With these radii improved by our muonic X-ray measurements, the g-factor measurements would become one of the strongest constraints for a certain class of 5th forces.
Recent preliminary experimental work by us has demonstrated that the most important experimental uncertainty originates from the nonlinearity of the best available ADCs to be used in the measurements of these X-rays. Improved X-ray energy calibration id therefore essential to achieve the ultimate experimental accuracy.
On the theory side, progress depends critically on a better understanding of nucleon and nuclear polarizabilities, which traditionally constitute the main systematic limitation. Intense collaboration between theory and experiment is therefore of utmost importance.

Thus, we propose to
(a) provide TA for the data taking at PSI and collaboration meetings for beam time preparations, laser development and data analysis. TA from this LOI amounts to 35 kEUR (28kEUR direct and 7k indirect costs).
(b) support travel for PhD students, Postdocs and PIs for preparatory work, training and to stimulate collaboration between QED and nucleon structure theory.
(c) support one summer school or workshop, with experts from muonic experiment, nuclear theory and detector physicists.

2. Connection to Transnational Access infrastructures (TAs) and / or Virtual Access projects (VAs)

PSI hosts the world's strongest negative muon beams, and we propose funding the PSI activities for muonic atoms (MagP and Mu4Rad) and neutron science (Fertl) as a transnational infrastructure, with a grand total of 140 kEUR, including indirect costs.
Note: This is the revised value, which is larger than the 100kEUR noted by Fertl
Muonic atoms are currently studied at PSI by the CREMA, HyperMu, muX, ReferenceRadii, QUARTET and MIXE Collaborations for a variety of hadron physics (CREMA and HyperMu study the proton charge and magnetic properties), light (QUARTET) to very heavy (muX) nuclei, and for applications of muonic atoms in trace element analysis and study of cultural heritage (MIXE). In addition, the neutron is studied in n2EDM and tauSPECT.

3. Estimated budget request

* Support for training and dissemination at conferences for PhDs, PD, and PIs of 2.5kEUR (2k direct, 0.5k indirect costs) per year per each of the 5 PIs = 40k + 10k = 60 kEUR

* Support for one Summer School / Workshop = 8k + 2k = 10 kEUR

* Support for transporting the complex and sensitive MMCs and dilution refrigerator from KIT Heidelberg to PSI and back, 2x over the 4-year funding period = 4k + 1k = 5 kEUR

* (TA: 28k + 7k = 35 kEUR)

4. Participating and partner institutions

JGU Mainz, Germany
KIP, Heidelberg, Germany
LKB, Paris, France
Technion, Haifa, Israel
Uni Leuven, Belgium
PSI, Switzerland
Uni Coimbra and Lisbon, Portugal
Close collaboration between theory and experiment is crucial.