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)

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. The German company Struck Innovative Systeme has agreed to investigate the possibility of designing a waveform digitizer with vastly improved ADC linearity.

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) fund development of improved microcalorimeters with better efficiency at energies between 50keV and 200keV, required for muonic K-X-rays in the region around Z=10. This development will be spearheaded at KIP, Heidelberg.

(b) fund development of an improved waveform digitizer with much better ADC linearity in collaboration with the German company Struck Innovative Systems.

(c) support travel between the collaborating institutions for preparatory work, such as X-ray detector calibrations, for data taking and analysis, and more.

(d) fund collaboration meetings and beam times at PSI for the collaborating institutes.

(e) organize two workshops, possibly at ECT*, MITP Mainz, LKB Paris, etc, that bring together theorists and experimentalists to fully exploit the precision possible using this novel measurement technique. A solid theoretical understanding of nuclear and nucleon polarizabilities, and their correlation between isotopes, is of greatest importance for the determination of absolute charge radii and charge radius differences from the isotope shifts.

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

PSI hosts the world's strongest negative muon beams, and we are exploring the possibility of proposing PSI as a transnational infrastructure. The MUSE experiment at PSI on elastic muon scattering on the proton is crucial for understanding the proton charge radius puzzle as well as measuring the two-photon exchange.
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. More conncetions to this HORIZON Call appear very possible.

For this LOI, we envisage travel support for extended data taking periods.

The vastly improved radii of the lightest nuclei will be of utmost importance for tests of QED and the Standard Model, searches for BSM physics, determination of Vud from mirror nuclei, and last not least for complementing measurements in elastic electron scattering at MAMI, MESA, JLab, PSI and elsewhere. Here, precise knowledge of the charge radii determined by muonic X-ray spectroscopy will be used to constrain fits of form factor measured in elastic electron scattering.

3. Estimated budget request

- 1 PhD student for data taking and analysis of muonic Ne (Z=10)
- 50 kUR for the development, manufacturing and characterization of improved microcalorimeters and SQUID electronics at KIP, Heidelberg.
- 120 kEUR for development and purchase of improved waveform digitizers (128 channels) from Struck, Germany
- 70 kEUR per year for travel for experiment preparations, data taking at PSI, data analysis and collaboration meetings
- For each of the planned two international workshops, we ask for 15k travel support.

4. Participating and partner institutions

JGU Mainz, Germany
KIP, Heidelberg, Germany
LKB, Paris, France
Technion, Haifa, Israel
Uni Leuven, Belgium
PSI, Switzerland
For theory support, we collaborate with K. Pachucki (Uni Warsaw) and V. Yerokhin (MPI Heidelberg). Further external collaboration with S. LiMuli (Chalmers), V. Patkos (Prague) and others is planned. Close collaboration between theory and experiment is crucial.