Letter of intent: **MagP - Magnetic properties of the proton and the deuteron**

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1. Research objectives

The rms charge radius of the proton has been under scrutiny for 15 years now, ever since our (CREMA Collaboration) measurement of the **Lamb shift** in muonic hydrogen differed by up to 7 standard deviations from the values determined in hydrogen spectroscopy or elastic electron scattering. Even though many (most?) people have accepted the muonic proton radius, there has not been a satisfactory explanation why both, H spectroscopy and e-p scattering seem to have found the wrong value. Most modern experiments in hydrogen spectroscopy agree better with the small, "muonic" proton charge radius, but of the new experiments only the PRad experiment at JLab has so far observed the small radius in elastic electron scattering.
The HyperMu Collaboration at PSI now aims at a measurement of the **hyperfine splitting** of the ground state in muonic hydrogen, which will give access to the so-called Zemach radius of the proton. The Zemach radius encodes the magnetic properties of the proton and can be also determined from combining the electric and magnetic form factors measured in elastic electron scattering. Notably, the magnetic structure of the proton is significantly harder to extract from elastic electron scattering than the electric structure, due to the suppression of the magnetic form factor at low momentum transfers. In fact, the proton rms magnetic radius has already been dubbed as the “new proton radius puzzle” [Lin et al. 2023, hep-ph/2312.08694], due to conflicting determinations from elastic scattering (dispersion-theoretical analysis and conventional fits) and lattice QCD. Therefore a cross-comparison of the Zemach radius may help understand the e-p scattering side of the "proton radius puzzle" and provide valuable lessons for past and future experiments at MAMI, MESA, JLab, PSI and elsewhere. Once this hyperfine splitting is completed, CREMA aims at a 5-fold improved determination of the proton charge radius.
The CREMA Collaboration has already measured the hyperfine splitting of the excited 2S state in muonic deuterium, and a significant 5σ discrepancy exists between experiment and theory using state-of-the-art nuclear models for the deuteron and polarizabilities for the proton and the neutron [PRA 98, 062513 (2018)]. Several more discrepancies exist in the hyperfine structure of molecules and molecular ions of hydrogen and its isotopologues (HD, HT, HD+ etc.). Since these systems are included in the CODATA determination of fundamental physical constants, accurate understanding of the magnetic properties of the proton and its isotopes is of great importance.
Measurements of the Lamb shift and hyperfine splitting in muonic atoms not only allow us to extract nuclear radii with unprecedented precision, but also provide unique probes of the Standard Model of particle physics (and possibly beyond) [NuPECC Long Range Plan, nucl-ex/2503.15575]. Combinations of different precision atomic-spectroscopy measurements, together with theoretical predictions of QED and weak corrections to the spectra, allow to determine nucleon- and nuclear-structure corrections empirically, thereby, benchmarking nuclear theory. In the case of the μD Lamb shift, the empirical value for the nuclear-structure corrections presently is a factor of four more precise than any state-of-the-art theory prediction. Therefore, to exploit the full potential of precision atomic spectroscopy to test bound-state QED and nuclear theories, as well as to refine the

determination of fundamental constants [Antognini et al., nucl-th/2210.16929], it is important to refine not only the dominating uncertainties from hadronic and nuclear corrections, but also the QED and higher-order recoil corrections. Inspired by the success of the “Muon g−2 Theory Initiative”, the μASTI Theory Initiative (Muonic Atom Spectroscopy Theory Initiative, https://asti.uni-mainz.de) has been launched in 2022 as a coordinated effort to support the experimental programs for the spectroscopy of light muonic atoms. The initiative aims to provide accurate theory predictions for light muonic atoms (initially hydrogen, deuterium and helium) to test fundamental interactions by comparing to electronic atoms. To date, μASTI has organized five workshops and is preparing a first community consensus paper for the theory prediction of the hyperfine splitting in muonic hydrogen. The initial review will help to identify limitations of the Standard Model theory predictions that should be improved in order to match the anticipated accuracy of future measurements.

We propose to
(a) fund one PhD student to contribute to the measurement of the hyperfine splitting in muonic hydrogen. In addition, this student will work towards modifying the HyperMu laser system for the new CREMA laser for the improved proton charge radius.
(b) fund two PhD students to work on theory. One within μASTI, to contribute to refinements of the muonic atom theory. This shall include, but is not limited to, refinements of two- and three-photon-exchange (TPE) corrections in muonic hydrogen, both for the hyperfine measurement (where TPE is the leading finite size "Zemach radius" effect) as well as for the Lamb shift, where the TPE is the limiting uncertainty in the proton charge radius determination. The 2nd PhD student will work on the nuclear structure contribution in muonic deuterium, both for the Lamb shift, where the two- and three-photon exchange with the nucleus are the dominant uncertainties for the deuteron charge radius determination, and for the hyperfine splitting, where the significant 5σ discrepancy with experiment exists.
(c) 200 kEUR for equipment and consumables required for an improved laser system for CREMA Phase 3.
(d) fund parts of the data taking at PSI and collaboration meetings for beam time preparations, laser development and data analysis.
(e) one workshop, with experiments and the muASTI theory initiative, to prepare a critical survey of the theory that can guide the hyperfine measurement and establish a trustworthy theory uncertainty of the result.

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 effects by comparison of μ+ p and μ- p (as well as e+ and e-) scattering.
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 connections to this HORIZON Call appear very possible.

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

The first measurement of the Zemach radius from muonic hydrogen will without doubt constitute a benchmark for both elastic form factors measured at MAMI, MESA, JLab, PSI and elsewhere, as well as critical test of our understanding of two-photon exchange in the proton. The improved measurement of the proton charge radius will require a 5-fold improved understanding of the proton polarizability to match the envisaged improved experimental precision.

3. Estimated budget request

- 1 PhD student for data taking and laser improvement
- 2 PhD students for theory in muonic hydrogen and muonic deuterium
- 200 kEUR for the development of an improved laser system for the next generation proton radius measurement.
- 70 kEUR per year for travel for experiment preparations, data taking at PSI, data analysis and collaboration meetings
- 15 kEUR for one international workshops, mainly travel support.

4. Participating and partner institutions

JGU Mainz, Germany
LKB, Paris, France
PSI, Switzerland
Uni Coimbra and Lisbon, Portugal
For theory support, we collaborate with V. Yerokhin (MPI Heidelberg). Further external collaboration with V. Patkos (Prague) and others is planned. Close collaboration between theory and experiment is crucial.