Letter of intent: **MagProton - Proton magnetic properties**

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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) 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 28kEUR direct and 7k indirect costs.
(b) support travel for PhD students, Postdocs and PIs for training and to induce collaboration between QED and nucleon structure theory.
(c) support one summer school or 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 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 4 PIs = 32k + 8k = 40 kEUR

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

* (TA: 40k + 10k = 50 kEUR)

4. Participating and partner institutions

JGU Mainz, Germany
U Warsaw, Poland
LKB, Paris, France
PSI, Switzerland
Uni Coimbra and Lisbon, Portugal
Close collaboration between theory and experiment is crucial.