Work package number [9]	WP15	Lead beneficiary [10]	1 - CNRS
Work package title	NA4-Proton Radius European Network (PREN)		
Start month	1	End month	48

Objectives

Objectives
The proton is the primary building block of the visible Universe, but some of its most elementary properties are not well understood. For example, its "size", i.e. the root-mean-square (rms) charge radius of the proton (Rp) has for years been believed to be about 0.88 fm, with 1% uncertainty. Two independent methods, elastic electron-proton scattering, and precision spectroscopy of atomic hydrogen yielded consistent results. In 2010, however, a measurement of Rp using the exotic "muonic hydrogen atom", resulted in a 10 times more accurate, but a 4% (corresponding to 5 standard deviations) smaller radius: Rp = 0.84 fm. Within the Standard Model, which assumes lepton universality, both probes must yield the same radius.
This so-called "proton radius puzzle" (PRP) has sparked great activity in both experiment and theory. The 2017 NuPECC Long Range Plan (LRP) thus calls for a dedicated, cross-disciplinary program involving experimental hadron and atomic physics, supported by renewed efforts in hadron and particle theory, as well as lattice QCD (LRP, page 62). Many ideas have been put forward to explain this striking discrepancy, such as incorrect radius extraction from scattering data, inaccurate hadronic corrections, or new physics effects such as lepton non-universality which would imply physics beyond the Standard Model. None of these are however widely accepted.
This motivates a reinforced world-wide effort, both experimental and theoretical. It combines atomic spectroscopy and lepton scattering, each involving both electrons and muons. The international effort on this matter concerns several leading groups in Europe. The network proposed here constitutes the critically missing forum between atomic spectroscopy and lepton scattering communities. It will provide the ideal framework to develop synergies, to draw common strategies and to enhance constructive collaborative theoretical and experimental research activities in order to converge together in attempting to solve the proton charge radius puzzle.
Besides, it will offer an environment of excellence for the training of students and young scientists in fields as diverse as atomic spectroscopy and lepton scattering, both in experiment and theory. Advances in theory are mandatory to guide, to interpret and to model experiments. This network will allow for a closer collaboration and fruitful exchanges between all theorists involved.
The framework of the proposed European network represents a unique and valuable opportunity to associate, for the first time, physicists involved in the understanding of hadron structure to shed new light on the actual proton charge radius puzzle, which has become even more intriguing given the recent results obtained on atomic hydrogen.

Description of work and role of partners

WP15 - NA4-Proton Radius European Network (PREN) [Months: 1-48]
CNRS, JGU MAINZ
Co-leadership : JGU Mainz

Description of work (where appropriate, broken down into tasks), lead partner and role of participants
Spokesperson: Dominique Marchand, Randolf Pohl
The PREN Network aims at providing a supporting structure to investigate the current discrepancy between various determinations of the proton charge radius. We have identified as the main missing ingredient to a comprehensive understanding and an ultimately solution of the PRP a lack of interaction and collaboration. We thus foresee the following tasks:
(1) Collaboration
(1.1) PREN-Collaboration:
Enhance collaboration between groups working in similar fields ("competing" groups), by funding exchanges of scientists, e.g. for participation in beam times / measurements, or joint analyses or publications. To allow outstanding Postdoctoral fellows and PhD students, to spend several months at a "competing" group. The aim is to migrate knowledge between different groups and provide new input to established procedures in these groups.
Provide funding to hire a postdoctoral fellow at JGU Mainz and to grant a PhD student for 18 months at CNRS (to be completed by another source of funding).
(1.2) PREN-Study: help fund extra studies (experimental and theoretical), e.g. for supporting systematics studies of experiments or comprehensive theory studies, e.g. in two-photon physics.

Elastic electron scattering off the proton determines the electric form factor, which can be interpreted, in the non-relativistic approximation, as the Fourier transform of the charge distribution of the proton. The rms proton charge radius is then obtained by determining the slope of the electric form factor versus Q2 in the limit where Q2 equals to zero. Up to now, this extrapolation is based on parametrizations of data sets with a minimum Q2 of the order of 10-3 (GeV/c)2. New high precision measurements at the lowest achievable Q2 values have been proposed, both in electron and muon scattering off the proton, in order to better constrain the form factor parametrizations. An intensive experimental program will be performed throughout Europe. Three electron scattering experiments are underway or proposed in Mainz (JGU): at MAMI, Q2 values down to a few 10-4 (GeV/c)2 will be reached using initial state radiation. Another experiment takes advantage of the active time projection chamber (TPC) designed at PNPI to detect low-energy recoil protons. The MAGIX experiment at the new MESA facility (Mainz) will provide charge and magnetic radii of the proton. In Orsay, the ProRad experiment at PRAE (Platform for Research and Applications with Electrons) aims to go down to a Q2 value of a few 10-5 (GeV/c)2 relying on a non-magnetic method like the PRad experiment which was performed at TJNAF (USA), the data analysis of which is underway.
Muon scattering on the proton has been approved at PSI and proposed at CERN. The MUon proton Scattering Experiment (MUSE) at PSI measures both electron and muon scattering, for both negative and positive leptons. At CERN, the COMPASS collaboration has very recently proposed to exploit its high energy muon beam to measure muon-proton elastic scattering at very low Q2 down to 10-4 (GeV/c)2. These measurements will test lepton universality and determine the two-photon exchange effects.
Ultra-high precision spectroscopy of atomic hydrogen has been performed by the groups of MPQ Garching and at the LKB, Paris. These measurements reach accuracies of parts in 1011 to 1015, and yield critical input for the CODATA adjustment of fundamental physical constants. Very recently, a new measurement from MPQ has underlined the urgent need for new measurements in the field.
Laser spectroscopy of muonic atoms (H, D) and ions (He+) have been pioneered by the CREMA (Charge Radius Experiments with Muonic Atoms) collaboration (MPQ, JGU Mainz, ETH Zurich, PSI and LKB). Due to the 200 times larger mass of the muon compared to the electron, muonic atoms are 10 million times more sensitive to nuclear size and polarizabilities. CREMA aims at extending the muonic measurements to the magnetic radius of the proton, and radii of other light nuclei. Several on-going laser experiments will help shed light on the PRP, such as spectroscopy of hydrogen molecules H2, D2, T2 and molecular ions H2+, HD+; He atoms and ions, Positronium and Muonium. Key players are the groups of LKB, VU Amsterdam, UCL, ETH Zurich, PSI, and MPQ. These measurements are sensitive either directly to Rp, or to the Rydberg constant, which is 100% correlated with Rp. They will also investigate the PRP using different nuclei such as the deuteron, triton, or helium nuclei. All these experimental efforts rely on calculations of atomic and molecular levels with accuracy in the 10-12 range.
Theoretical activities are required to guide, to interpret and to model experiments. In Spain (UAB/IFAE), Germany (MPQ, JGU Mainz) and France (LKB Paris), teams investigate nuclear effects in light nuclei. The JGU Mainz theoretical group focuses on the higher-order radiative contributions (also GW University, USA) and polarizability effects in lepton scattering and atomic physics. On the atomic and molecular physics side, the accuracy of H-like, few-body and molecular systems are going to be improved (Warsaw, Garching, Paris, Dubna). This NA will allow for a closer collaboration and fruitful exchange between theorists from atomic physics and lepton scattering.
(2) Meetings
(2.1) PREN-Conventions: a kick-off meeting to identify the most pressing questions. Two more workshops will be organized where all PREN groups will present results. Detailed discussions and targeted sessions will scrutinize the results in great detail, and provide guidance for more in-depth studies.
(2.2) PREN-Meet: organization of working meetings or targeted workshops dedicated to specific sub-topics relevant for the proton radius puzzle.

Participation per Partner

Partner number and short name	WP15 effort
1 - CNRS	4.80
9 - JGU MAINZ	9.60
Total	14.40

List of deliverables

Deliverable Number[14]	Deliverable Title	Lead beneficiary	Type[15]	Dissemination level[16]	Due Date (in months)[17]
D15.1	PREN website	1 - CNRS	Websites, patents filling, etc.	Public	6
D15.2	PREN-WP	1 - CNRS	Report	Public	48

Description of deliverables

D15.1- PREN website
D15.2- PREN-WP

D15.1 : PREN website [6]

D15.1- PREN website: development of a dedicated website to be available by Spring 2019 (a) to advertise PREN and to announce events publicly, (b) to share information between all PREN participants with specific pages according to topics, to keep track of convent and workshop materials [Restricted access by password] (month 6).

D15.2 : PREN-WP [48]

Co-leadership : 9. JGU MAINZ D15.2- PREN-WP: a white paper (WP), gathering all significant results obtained over the network duration by the joint activities of all participants, shall be written towards the end of the funding period (end 2022) with (a) either the solution of the proton radius puzzle, and the lessons to be learned from this large discrepancy, or (b) a global strategy that promises the highest chance for the solution of the proton radius puzzle (month 48).

Schedule of relevant Milestones

Milestone number[18]	Milestone title	Lead beneficiary	Due Date (in months)	Means of verification
MS17	Development of a dedicated website	1 - CNRS	6	Access availability
MS18	Conventions	1 - CNRS	45	Convention, due dates (in months): 3, 24, 45
MS19	Meetings	1 - CNRS	33	Targeted workshop organization, due dates (in months) : 15, 33