Letter of intent: tSPECT – measurement of the free neutron lifetime to test test hadronic contributions to electroweak precision observables (precision section)

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1. Research objectives

The lifetime of the free neutron is a fundamental property of the only unstable nucleon. It allows precision tests of the neutron's electroweak and strong structure and provides for highly sensitive searches for physics beyond the Standard Model (BSM). Currently the most precise determination of the CKM matrix element V_{ud} is based on $0^+ \rightarrow 0^+$ super-allowed nuclear beta decay measurements with large uncertainty contributions from nuclear structure descriptions. Without nuclear structure corrections, V_{ud} can be determined from the combination of the free neutron lifetime τ_n and the measurement of the ratio of the axial-vector-to-vector coupling constant λ, also in neutron decay. On the theory side the description of the neutron decay at the desired level of 10^{-4} precision must consider the hadronic effects on the evaluation of the radiative corrections to the charged current matrix element and the so-called γW-box diagram. On the experimental side, the neutronic determination of V_{ud} requires the measurement of the τ_n with an uncertainty of less than 0.1 s. Currently, experimentally complementary techniques extracting the neutron lifetime either from the decay activity of a cold neutron beam or from the storage of so-called ultracold neutrons (UCN) resulted in the neutron lifetime puzzle, a discrepancy of more than 8 s compared to the most precise measurement of τ_n = 877.94+/-0.37 s provided by the UCNτ collaboration. UCNs have kinetic energies in the range between 0 and 350 neV, on the same scale as their gravitational interaction energy (102 neV/m) or their magnetic moment (61 neV/T). Therefore, UCN can be confined in magnetic bottles formed from suitable materials or from a combination of strong magnetic field gradients and gravity or purely magnetic field gradient arrangements. The later configuration is used by the tSPECT collaboration to fill a magnetic trap with UCN by time-dependent spin flips and subsequent storage of the UCNs for variable times. At the end of the storage time an in-situ UCN detector is pushed into the storage region to count the remaining UCNs. At JGU Mainz we have established the trap loading scheme using spin flips before transferring the experiment in 2023 to the UCN source of the Paul-Scherrer-Institute (PSI) Switzerland to profit from the source's outstanding UCN output performance and beam time availability. With tSPECT we anticipate continuing data taking at PSI throughout 2026 to reach an uncertainty of less than 0.3 s. Even with its first results, tSPECT will be able to illuminate the neutron lifetime puzzle independently. As tSPECT is a prototype experiment paving the way, we aim to maximize the UCN phase space acceptance by scaling up the trap in physical extent and magnetic depth in a follow up experiment. Besides an improved experimental setup, we will profit from the refurbishment of the PSI UCN source 2028. Together with improved control offer accidental UCN loss channels from the magnetic neutron trap, this will allow us to reduce the uncertainty on τ_n to 0.1 s in the future.

To support the successful measurement of the neutron lifetime with an uncertainty of 0.3 s within the duration of the EU action, we propose to

(a) fund developments of highly segmented, in-situ, cryogenic and magnetic field compatible UCN detectors that will be able to count the increased number of UCN pile-up free. This development will be spearheaded at PSI.
(b) fund a PhD student to complement the team performing the data analysis of the stored UCN data to extract an independent neutron lifetime result to scrutinize the results of the UCNτ collaboration.
(c) Fund travel between the collaborating institutions for preparatory work, for data taking and analysis, and more
(d) fund collaboration meetings and beam times at PSI for the collaborating institutes.

(e) fund the organization of two workshops, possibly at ECT*, MITP Mainz, PSI that bring together theorists and experimentalists to fully exploit the precision anticipated through the fully magnetic storage of UCNs. A solid theoretical understanding of nuclear and nucleon properties is indispensable to reliably extract the matric element V_{ud} at the a 10^{-4} level of precision or to interpret any deviations between experiment and SM theory as indication of BSM physics.

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

PSI hosts one of the world's most intense source of UCNs. This source currently supplies the tSPECT and the n2EDM experiments pushing the low-energy frontier of particle physics by unprecedented statistical sensitivity and systematic control of the experimental environments. PSI also provides the world's strongest source of muon beams. In particular, the negative muon beams are currently used by the CREMA, HyperMu, muX, ReferenceRadii, QUARTET and MIXE collaborations for a variety of studies in the fields 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). Therefore, we propose to include PSI as a transnational infrastructure.

3. Estimated budget request

- 1 PhD student for data taking and analysis UCN data taken with the tSPECT experiment (3 years, 75% FTE, 210 kEUR direct costs, 52.5 kEUR indirect costs)
- 40 kEUR per year for travel for experiment preparations, data taking at PSI, data analysis and collaboration meetings (4 x 30 kEUR =120 kEUR direct costs, 30 kEUR indirect costs)
- For each of the planned two international workshops, we ask for 15k travel support (30 kEUR direct costs, 7.5 kEUR indirect costs

Total budget: 360 kEUR direct costs and 90 kEUR indirect costs over 4 years.

4. Participating and partner institutions

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Paul Scherrer Institute, Switzerland

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