Expression of Interest for an ApPECC-ECFA-NuPECC Synergy Project

Storage Rings for the Search of Charged-Particle Electric Dipole Moments (EDM)

Abstract:

We propose a storage ring to search for electric dipole moments of charged particles with unprecedented sensitivity. This requires the design of a new type of accelerator namely an all-electric storage ring capable of simultaneously maintaining clockwise and counter-clock-wise polarized beams – a prime task for the accelerator community. The EDM observable is embedded in the time development of the beam polarization, a quantity studied in many nuclear/hadron physics experiments. The scientific case rests upon non-electroweak CP-symmetry violation and the related strong CP-problem; additional CP-violation will elucidate the matter-antimatter asymmetry puzzle of the Universe, which falls into the realm of particle and astroparticle physics. Oscillating EDMs are an additional subject-of-study to search for axion/ALP Dark Matter, one further outstanding question of contemporary subatomic science. This proposal thus constitutes a prime example for a possible cooperation between the JENAS communities.

1. Scientific Background

Permanent Electric Dipole Moments (EDM) of particles violate both time reversal (T) and parity (P) invariance and, on the basis of the CPT theorem, they also violate the combined symmetry CP (CPV). Such a symmetry breaking is thought to be responsible for the different behavior of particles and antiparticles, leading, e.g., to the apparent matter-antimatter asymmetry in the Universe. CPV is found in the electroweak part of the Standard Model of particle physics (SM) but, since SM-CPV is much too weak to explain the matter-antimatter asymmetry, other sources must be sought. An obvious observable to investigate is an EDM – finding a finite EDM would very probably also indicate new physics, not contained in the SM. After a possible discovery of an EDM, different systems will have to be investigated in order to identify the CPV-source. Because of its exceptional science case, EDMs are searched for in various systems, hitherto, e.g., for the electron bound in atoms and molecules or the free neutron, but only impressive upper limits have been obtained so far. Recently, it has been proposed to use polarized charged particles, like proton, deuteron and ^{3}He, confined in a storage ring. The measurement principle is based on the time development of the polarization vector – which is parallel to the EDM – subject to a radial electric field: a beam of particles, originally polarized horizontally, slowly develops a vertical component. In spite of its simplicity, this represents an enormously challenging project due to the smallness of the expected effect.

As of late, oscillating EDMs as an additional observable have come into focus: axions and axion-like particles (ALPs) induce such oscillating EDMs with an oscillation frequency proportional to their mass. Since these yet unobserved particles are well motivated candidates for dark matter (DM) with largely unconstrained mass, they are also searched for with different approaches: srEDM storage rings are very well suited to join these searches over a wide range of mass/oscillation frequency. To observe axions/ALPs, the particle spins have to precess at the oscillation frequency to produce a resonance build-up of the vertical polarization. It should be noted that this principle can already be applied in storage rings with magnetic bending, such as COSY (Jülich, Germany), and that it is less sensitive to systematic effects compared to the static EDM case.

2. Objectives

As inferred from previous measurements, e.g., for the neutron, the smallness of EDMs requires significant efforts to further improve the experimental upper limits – ultimately to an EDM sensitivity of the order of 10^{-29} e cm. For the proton this implies the design and construction of a dedicated all-electric precision storage ring which can store clockwise and counter-clockwise horizontally polarized beams simultaneously. The momentum of the beams should be "magic" (700.7 MeV/c, corresponding to 232.8 MeV) in order for the precessing spin due to the magnetic dipole moment always pointing along the momentum direction ("frozen spin condition"). Deuterons and ^{3}He measurements will require a combination of E- and B-fields to fulfill this condition. For technically feasible electric fields the circumference of such a ring will be a few hundred meters (8 MV/m □ 500 m). There are further technological and metrological challenges that need to be mastered, e.g., storage and spin coherence time of the beams, residual radial magnetic fields which mimic an EDM, or the required precision of beam position monitors. The conclusion of the JEDI- (Jülich Electric Dipole moment Investigations) and the CPEDM- (Charged-Particle EDM) collaborations is that this requires a stepwise approach:

- Step-1: Proof-of-capability (this is an ongoing effort of the JEDI-collaboration)
  COSY-Jülich is a worldwide unique storage ring for polarized beams with magnetic deflection: (i) perform a first-ever deuteron EDM „precursor experiment", (ii) conduct a proof-of-principle for axion/ALPs search, (iii) optimize the proton spin-coherence time (SCT).
- Step-2: Proof-of-principle
  Design, build and operate a prototype ring (beam energy ~40 MeV) in two steps: (i) an all-electric ring for CW/CCW operation, but not at the magic momentum, (ii) complement ring with B-fields for „frozen spin"; perform first competitive proton (pEDM) experiment (with a sensitivity similar to the neutron EDM).
- Step-3: Precision experiment
  Design, build and operate a dedicated storage ring (all-electric, 232.8 MeV) to push the pEDM sensitivity significantly below that of the neutron EDM; the final goal is 10^{-29} e cm.
- Optional step-4: Measurements with additional ions (deuteron, ^{3}He)

This will require a ring with combined E- and B-fields for the “frozen spin“ condition.

The objective of this EoI is to convene and combine technological and scientific expertise in accelerator, nuclear/hadron and particle physics for a storage-ring EDM project. The emphasis will be on Step-2 as the inevitable milestone towards Step 3:

- Prepare a technical design study (TDR) for the prototype ring, then build and operate it. It should be host-site independent, in particular not require COSY as injector.
- Conduct a pEDM measurement as proof-of-principle and pave the way for the design of the final high-precision ring.
- In addition: exploit the prototype ring to conduct a Dark Matter (axions/ALPs) scan by searching for oscillating EDMs.

Work packages:

- Science case
    - Static EDM search for proton (deuteron and ^{3}He)
    - Oscillating EDMs for axion/ALP search (Dark Matter)
    - General relativity effects on spin motion (based on full Thomas-BMT eq.)
- Design Study for prototype ring
    - Ring layout
    - Storage ring elements (benders, injection kicker, quadrupoles)
    - Key instrumentation (diagnostics, spin manipulation tools, polarimeter, phase space cooling, rf cavity)
- Technical design report
    - Costing, host lab options
    - Systematic limitations
    - Risk assessment and mitigation
    - Roadmap
- Prototype procurement, commissioning and exploitation

3. Cooperation

The project to measure permanent EDMs of the proton and light ions (deuteron, ^{3}He) is at the intersection of nuclear/hadron and particle physics. For its realization, a strong involvement of accelerator physics is required. Particle-based Dark Matter, which can be searched for over a wide mass range by oscillating EDMs, is an important issue for astroparticle physics. Thus, this EoI constitutes an excellent opportunity of a possible cooperation within JENAS (ApPECC-ECFA-NuPECC).

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References:

F. Abusaif et al. (CPEDM collaboration), *Feasibility Study for a Storage Ring to Search for Electric Dipole Moments of Charged Particles*, arXiv:1812.08535

Also see: The European Strategy Group, *Deliberation Document on the 2020 update of the European Strategy for Particle Physics* (p. 16), June 2020