COMITÉ NATIONAL DE LA RECHERCHE SCIENTIFIQUE
CONSEIL SCIENTIFIQUE D'INSTITUT

Report

Scientific Council of IN2P3
Session of 24-25 June 2024

Table of contents

Precision measurements and testing of fundamental interactions and symmetries

1. Organization

The meeting took place on 24-25th June 2024, in person at IPHC, Strasbourg.

Participants:

Scientific Committee members:
Navin Alahari, Nicolas Arbor, James Bartlett, Auguste Besson, Olivier Bourrion, Emmanuel Clément, Barbara Clerbaux, Maria De Los Angeles Faus-Golfe, Maria José Garcia Borge, Jules Gascon, Andrea Jeremie, Yoann Kermaïdic, Iro Koletsou, Aleandro Nisati, Isabelle Ripp-Baudot, Laurent Serin, Vincent Tatischeff, Dominique Thers, Frédéric Yermia
Excused: Didier Laporte, Nicolas Leroy, Luc Perrot

Members of the IN2P3 direction:

Marcella Grasso and Laurent Vacavant, Scientific Deputy Directors of IN2P3 (DAS)

External reviewers:

Alessandro Baldini (INFN Pisa), Gabriel Chardin (APC Paris), Daniel Comparat (LAC ORsay), Martín González-Alonso (IFIC Valencia), Michael Jentschel (ILL Grenoble), Bastian Märkisch (TUM München), Jonas Rademacker (Univeristy of Bristol)

Speakers:

Introductory talks: Ana Teixeira, Bertram Blank
Projects: Xavier Fléchard, Maud Versteegen, Leendert Hayen, Pierre Delahaye, Thomas Lefort, Guillaume Pignol, David Lunney and Cristina Carloganu.

2. Introduction and framework

A number of teams from IN2P3 are currently engaged in scientific endeavors focused on exploring fundamental interactions and symmetries.

In **particle physics**, the different projects are grouped together in the **"Precision Tests of Fundamental Interactions"** program (PTFI), which primarily addresses three key themes:

- Investigating the electric dipole moment of the neutron through the upgraded n2EDM experiment at PSI;
- Detecting charged lepton flavor violation via the COMET experiment, utilizing the powerful muon beam at J-PARC;
- Measuring the gravitational acceleration of anti-hydrogen, particularly through the GBAR experiment at the antiproton decelerator within the AD+ELENA complex at CERN.

All three projects—n2EDM, COMET, and GBAR—are set to undergo evaluation.

In the field of **nuclear physics**, low-energy precision tests of **β-decay processes**, which may uncover new physics beyond the standard model (BSM), are garnering significant interest from the international community. Numerous projects are currently underway across various international facilities in locations such as the United States and Europe. In Europe, and particularly in France, these scientific endeavors are being seamlessly incorporated into the DESIR low-energy installation, which is currently under construction at GANIL-SPIRAL2 and is expected to start operations around 2027. This facility's precise measurements of beta decay are a pivotal part of its scientific focus. Four experiments—bSTILED, MORA, WISArD, and the ASCARD proposal—are set to be evaluated. The IN2P3 laboratories contribute to these initiatives in varying capacities, with each project at different stages of development.

3. Agenda

All of the projects mentioned earlier were presented one month in advance with comprehensive documents following a proposed template. An oral summary of these documents was presented during the open session of the scientific council. Before the presentations, overviews of the phenomenological context and the current status of the DESIR installation at GANIL were provided. The session was structured into two thematic sections:

- ‘β-decay and precision measurements’

bSTILED (Xavier Fléchard, LPC Caen), 25 +10 mins
WISArD (Maud Versteegen, LP2I Bordeaux), 25 + 10 mins
ASCARD (Leendert Hayen, LPC Caen), 25 +10 mins
MORA (Pierre Delahaye, GANIL), 25 +10 mins

- ‘PTFI’

n2EDM (Thomas Lefort, LPC Caen, and Guillaume Pignol, LPSC Grenoble), 40 + 15 mins
GBAR (David Lunney, IJCLab Orsay), 35 + 15 mins
COMET (Cristina Carloganu, LPCA Clermont-Ferrand), 40 + 15 mins

More details are given in:
https://www.in2p3.cnrs.fr/fr/le-conseil-scientifique-de-lin2p3
https://indico.in2p3.fr/event/32648

4. Scientific Council charge and questions

The scientific council of IN2P3 has been asked to assess the progress of various projects, evaluate their potential scientific significance, and, if applicable, offer insights regarding the participation of the institute's researchers. More specifically, the inquiries directed by IN2P3 to its scientific council for all projects are as follows:

1) Within the context of the national foresight initiative of IN2P3, twelve "Science Drivers" (SDs) have been identified. The council is tasked with evaluating the current and anticipated impact of these projects on the respective SDs, which include:

a. "Continue searching for unknown particles and interactions (new phenomena)"
b. "Investigate matter-antimatter asymmetry and flavor transitions (flavor)"

The unique characteristics of each project pertinent to these SDs will be detailed, including how the projects complement one another. What are the expected scientific results and the overall influence of the project on the SDs?

2) What are the key characteristics (strengths / weaknesses) of the project within the global landscape in terms of scientific outcomes and influence, as well as in relation to technological advancements?

3) Does the team's dedication to the project meet expectations? Is it adequate to fulfill the outlined goals? Can we anticipate significant scientific contributions?

5. Precision measurements of nuclear beta decays

The projects bSTILED, WISArD, ASCARD and MORA are high-precision experiments, all investigating selected aspects of β-decay of specific nuclei using unique techniques. Measurements of these high-precision experiments are commonly described using Effective Field Theory (EFT). This assumes that any new physics beyond the known Standard Model (SM) happens at an energy scale far beyond the one accessible to the experiments, and hence can be described mainly model-independently by a fixed set of additional operators of given dimensions, and by corresponding Wilson coefficients. Experiments are consequently optimized to determine or provide limits on the Wilson coefficients. The hierarchy of EFTs allows a direct comparison of results to experiments at much higher energies, such as those done at the Large Hadron Collider. Wilson coefficients of the EFT used for beta decays can indeed be directly related to coefficients in the larger set of the Standard Model EFT (SMEFT), which is commonly used to interpret LHC data. The sensitivity of all projects discussed here in this thematic block is clearly internationally competitive and projects are complementary. The projects are also sensitive to interesting SM physics (e.g., the V_{ud} extraction).

5.1 The bSTILED project

Introduction and highlights

The **bSTILED (b**eyond standard model **S**earch for **T**ensor **I**nteractions in nuc**l**ear b**E**ta **D**ecay) experiment aims to obtain leading limits on exotic tensor interactions at the level of $\approx 2\times10^{-4}$ via a measurement of the Fierz interference term, *b*, in the beta decay of ^{6}He at a precision of 1×10^{-3}.
It requires a measurement of the energy spectrum of the β particles with a low threshold. The ambitious goal exceeds the sensitivity projection of measurements of the tensor coefficient at the LHC-Run3 by a factor of two, and would constitute an improvement by a factor of five with respect to the leading radiative pion decay experiment (PIBETA, PRL 2009). As a pure Gamow-Teller interaction, the decay of ^{6}He is only sensitive to tensor contributions and hence complements limits on scalar interactions from super-allowed nuclear decays. The high endpoint energy of ^{6}He (Q=3.5 MeV) is both an asset, since it limits the effect of Coulomb corrections, and a challenge, due to the lack of electron conversion calibration sources at high energies.

In the present phase 1, the team is attacking the problem using implanted ^{6}He at two different depths in the same YAP(Ce) inorganic scintillators through two experiments done at different energies using different setups. These different depths are achieved by using two energies of the short lived (~820 ms) ^{6}He beam at GANIL. In the first setup at low energy (25 keV), ^{6}He beam is implanted into the first scintillation detector and a complementary detector is brought in a timely fashion to complete the detection setup. In another independent experiment at higher energy (300 MeV), the ^{6}He beam is directly implanted in the scintillator. These two setups largely eliminate the issues of solid angle coverage and backscattering in the measurement of the emergent beta particle. The low detection threshold of the detector makes it possible to largely decorrelate the calibration from the physics signal, i.e. the Fierz term. The challenge of the escaping Bremsstrahlung radiation produced by the slowing down of the β particles remains. The linearity of the detector light collection is optimized by the selection of the scintillator material.

Comments

bSTILED is a very interesting and mature project searching for tensor interactions (*b* parameter in the nuclear β decay rate of ^{6}He), by studying the beta decay spectrum at the 0.1% level of precision. Although it uses relatively simple nuclear spectroscopy techniques, it has the potential to compete with LHC for constraining the tensor coefficient. This very experienced team from LPC Caen has a proven track record in this field. The project so far obtained the most precise half-life of ^{6}He and performed first measurements using low and high energy beams to analyze and compare systematic effects. First results of the low energy measurement have been presented at conferences and the data analysis is expected to be completed by 2024. Results from the high-energy implantation are under investigation, and will serve as a guidance for the measurement in the next project phase in order to obtain the targeted final precision.

The team is well aware of various limitations and is currently addressing them including the escape of the Bremsstrahlung radiation, as well as the remaining major one of non-linearities in the light collection. Competitive results for the Fierz term are expected within this year (2024), and the careful evaluation of the theoretical errors appears to be well under control. Compared to other worldwide projects aiming to extract the *b* term from the β decay spectrum, bSTILED is a solid project, with a good balance between innovation and risks. No major risk has been identified at this stage. The team's strength and track record are well aligned with the project's ambitious goals. The project that constitutes a collaborative effort of three French Institutes, GANIL, LPC and LNHB is supported by the ANR until March 2026. Neither equipment funds nor human resources are requested to IN2P3, in addition to the PhD thesis position currently funded by the Institute.

Recommendations

● The scientific council strongly supports this endeavor and looks forward to world leading results.
● The scientific council also recommends the team to start planning for Phase 2 which will build on the comparative study of the present work.

5.2 Activities in the WISArD experiment

Introduction and highlights

The **WISArD** (**W**eak **I**nteraction **S**tudies with ^{32}**Ar D**ecay) project searches for exotic scalar currents, by extracting both the angular correlation coefficient *a*, and the Fierz term *b*, in the nuclear β-decay of ^{32}Ar at a high precision level of 0.2-0.1% in the same experiment. This level of precision is very competitive and complementary to high precision experiments at IN2P3 searching for physics beyond the SM without colliders.

WISArD's unique feature is the use of the beta-delayed proton emission from the super-allowed decay of ^{32}Ar to the isobaric analog state in ^{32}Cl, which decays almost instantaneously ($t_{1/2}$ = 0.033(8) fs) via the emission of a 3.4 MeV proton. Thus, the determination of the low energy nuclear recoil is inferred from the measurement of the high energy proton, which in turn serves to determine the neutrino momentum distribution. The main observable is the energy distribution of the proton emitted after the β-decay of ^{32}Ar, which allows for the extraction of the *a* and *b* parameters. The measurement of *a* at the 0.2% level would provide the best constraint on scalar interactions involving right-handed neutrinos. The statistics required to reach such a precision have already been acquired in May 2024 after a recent experimental upgrade, and the analysis is ongoing.

The WISArD setup is installed in the ISOLDE experimental hall, at CERN where the ^{32}Ar beam ($T_{1/2}$ = 98 ms) was implanted. It consists of a 9 T superconducting magnet, within which a detection setup is installed, comprising eight Double-Sided Silicon Strip detectors, a Micro-Channel Plate detector and a Faraday cup. This setup is used for the measurement of the angular correlation between the two leptons. In order to measure the β spectrum shape, the high magnetic field is used to obtain a 4π detection geometry by confining backscattered beta particles in the detection region. This is similar to what is implemented in the PERKEO neutron beta decay experiments. The proof-of-principle measurement achieved in 2018 with the already existing equipment provided a result with a 4% relative precision. During the long shutdown of the CERN accelerator complex, an upgrade of the detection system was installed for the protons, which improved the solid angle coverage by a factor 7 up to 50%. With this improved system, data were taken in 2021 with a largely improved efficiency of beam transport and increasing the statistics by a factor of two. This dataset allowed the WISArD team to perform a detailed and still ongoing review of the systematics. Building on this campaign, a two-year period was devoted to further improving the setup and focusing on reducing systematics errors (beam shape measurement, mapping of detector dead layers and resolution, electron detector response, beam catcher, …). In 2024, during a successful data taking run of 10 days, with the full detector operating at nominal resolution, isobaric analogue state single proton events were detected. This will yield 0.2 % precision. A 0.1% level precision will be obtained from extra additional data from the same experiment in 2025 if systematics errors can be kept under control.

New β-decay spectrum shape measurements for various other isotopes are planned within the next 3 years with upgraded Si(Li) detectors that will feature improved energy resolution and reduced detection threshold. Among them it is relevant to mention the study of ^{14}O β-decay to improve the uncertainty on the branching ratio of the $0^+ \rightarrow 0^+$ superallowed transition by a factor 2 to 3. ^{14}O along with ^{10}C are the two superallowed $0^+ \rightarrow 0^+$ decays that have the greatest weight for obtaining the most stringent limit on scalar currents to date.

Comments

The members of the WISArD team have taken the necessary technical steps to accomplish the highest precision from the 2024 data. The scientific council appreciates the sustained efforts put in over the years by the collaboration to reach the present stage. It encourages the team to complete the on-going analysis as soon as possible to achieve world leading results in precision searches for beyond-standard model signatures.
Moreover, the scientific council also acknowledges the analysis strategy set for refining the understanding of systematics effects of present and future measurements and for keeping them under control. The scientific council considers important the measurement for ^{14}O β-decay and encourages the team to realize it as soon as possible. The activities at ISOLDE are well planned and implemented, hence the scientific council strongly supports the required financial support for travels and stays at CERN.

The present setup at CERN cannot be used at GANIL without major modifications. Presently there is no clear path defined for the large amount of funding required for the development of an equivalent setup at GANIL. The eventual availability of the nuclei to be studied at GANIL, namely ^{20}Mg would allow for a further increased sensitivity to scalar currents.

Looking ahead to the future of this program and taking into account the coming retirement of expert senior members of the team, the scientific council would like to point out that the current team needs to be reinforced with adequate technical staff and full-time researcher(s) in order to keep viable this high impact program in the long term. Together with IN2P3, the team needs to decide on a suitable strategy in order to avoid a loss of impact in this competitive field but also on the future work to be done at GANIL.

Recommendations

● The scientific council strongly supports the required financial support for travel and stays at CERN.
● The team needs to plan a suitable strategy of personnel replacement in order to keep a competitive program and avoid a loss of impact in this field, as well as to think on the future work to be done at GANIL.

5.3 The ASCARD project

Introduction and highlights

The ASCARD project aims to test the Standard Model by detecting sub-keV nuclear recoils from rare-short-lived isotopes implanted into Superconducting Tunnel Junction (STJ) quantum sensors. It proposes to use STJ sensors for two types of high-precision observables:

- the recoil spectrum following β decay, to extract the β-neutrino angular correlation
- the relative branching ratios of the Electron Capture (EC) and β+ decay modes, to extract the Fierz interference term

STJs are high-rate quantum sensors that were originally developed for high-resolution X-ray spectroscopy. STJs are a type of Josephson junction that consists of two superconducting electrodes separated by a thin insulating tunneling barrier. The high energy resolution in STJs is obtained thanks to the small energy gap of order 1 meV and thus roughly three orders of magnitude smaller than the band-gap in semiconductors. It gives rise to $\sim 1 - 10$ eV energy resolution for signal below 1 keV that are the relevant ones to this proposal. The STJ pixel detector operates at rates up to 10^4 counts/s, which places them among the highest rate quantum detection technologies with high energy resolution. Calibration and linearity can be precisely measured using lasers. The final measurement consists in a counting experiment with clearly distinguishable signals. The use of STJs for sterile neutrino physics was pioneered by the BeEST (Be Electron capture in Superconducting Tunnel Junction) experiment that reached sensitivity down to a few eV in the recoil energy spectrum. Presently the study of exotic nuclear recoils is part of the SALER (Superconducting Array for Low Energy Radiation) experiment that will be proposed at the Facility for Rare Isotope Beams (FRIB at MSU).

The ASCARD project aims to perform on-line measurements of recoil spectroscopy with the potential of per-mille level determinations of the CKM matrix element V_{ud} and of exotic tensor couplings. It is proposed to take advantage of an STJ detector to perform high precision low energy spectroscopy, combining technological advances and previous know-how from SALER. Currently STJs are the only sensors that can perform on-line, precision sub-keV spectroscopy using radioactive isotopes without half-life constraints. The recoiling nucleus in β decay is the only decay product whose energy spectrum is directly sensitive to the β-ν correlation even in the absence of other information, making it a unique probe. In the case of an electron capture decay (very low Q-value < 1.022 MeV for proton rich nuclei), the recoiling ion emerges mono-energetically and creates a distinct set of peaks. Even in decays where the β^+ particles also contribute, the distinction of the mono-energetic EC recoil peak will depend more on the background rate than on the precision of the underlying β^+spectrum. The analysis remains largely independent of the energy response function and of the β particle scattering such that it is eventually a simple counting experiment. Due to the 100% efficiency of the detection of the recoiling ion, and to the high-fidelity calibration of the STJ sensor, the ASCARD project is highly competitive compared to other approaches where the β-ν correlation is measured by other means.

The second goal of ASCARD is to reach the top row of CKM unitary tests as the continuous recoil spectrum following β-decay is sensitive to the Fermi/Gamow-Teller mixing ratio ρ, of importance for the extraction of V_{ud} from mixed transitions. From the recoil energy spectrum, a precise measurement of the mixing can be used to extract V_{ud} for mixed Fermi/Gamow-Teller decays using measurements of the half-life and Q-value of the decaying nucleus. Spectroscopy measurements of emitted β particles usually suffer from (back)scattering corrections and unresolved non-linearities. The scattering of β particles as they exit the detector is anticipated to be a significant systematic effect that will be mitigated by using Aluminium-based STJ detectors. Moving to Aluminium- rather than Tantalum- or Niobium-based STJ sensors is a major component of the ASCARD program, to address the leading systematic effects anticipated in the SALER experiment @ FRIB. The BeEST collaboration has already been working on the Al based STJ sensors, but for the search of heavy neutrinos. The study of low-*A* (mass number) mirror nuclei has significant advantages, as isospin symmetry inside the doublet transition fixes the dominant matrix elements, and cancellations provide significant enhancement in sensitivity in obtaining ρ (F-GT mixing ratio). Additionally, because of their low *A*, these nuclei are getting at reach for nuclear ab-initio methods. The latter in turn will be crucial in the coming decade to improve the precision of the nuclear structure corrections to V_{ud}. Promising candidates include the β^+ decays of ^{11}C, ^{13}N and ^{15}O with precisely known Ft values. They are easily produced, and are optimal as far as sensitivity to ρ is concerned.

There are various different experiments using neutrons and radioactive isotopes that perform precision β energy spectroscopy and recover angular correlations between final states, enabling the transition matrix element to be extracted and obtaining some sensitivity to exotic scalar or tensor currents. They reach percent-level sensitivity to Fierz term and in a single-experiment sensitivity between the percent and the per-mille level for the a or b parameters. Experimentally, dominant uncertainties in precision spectroscopy arise from backscattering and unresolved non-linearities in the energy calibration. The ASCARD project pioneers a new method in nuclear β decay investigations to overcome these problems.

Comments

The ASCARD project has the potential to have an important impact in precision measurements using beta decay probes. The main objective is to measure the recoil spectrum using STJ sensors. The proposed outline of the program seems adequate and currently focuses on a proof-of-principle due to further improvements in technological aspects of the STJ and on a study of systematic effects. At the same time, the scientific council considers important to get first the results from the recently started SALER project at FRIB, of which the proponent is also the co-spokesperson. Presently it is proposed to directly buy the STJs from the United States. However, it seems important to investigate the status of French/European market to identify possible production of these quantum sensors. Moreover, the availability of the relevant technical expertise for ASCARD at LPC Caen needs to be evaluated.

Recommendations

● The scientific council recommends that the team prepares a detailed study of the technical challenges, in particular the cryogenics infrastructure and its running/maintenance plan, given the specific constraints at GANIL for a future installation at DESIR.
● Considering the current modest size of the teams involved in ASCARD, the scientific council SC strongly recommends that the team clarifies the possible synergies and interferences of this new project, especially with the already on-going activities on the SALER and the MORA projects.

5.4 Activities in the MORA experiment

Introduction and highlights

The **MORA** (**M**atter's **O**rigin from **R**adio**A**ctivity) experiment primarily aims to measure the time-violating *D* triple correlation coefficient, relating the spin of the nucleus, with the neutrino and the electron momenta in β-decay. It is hence sensitive to CP-violation. Searches for new sources of CP violation are at the forefront of particle physics and essential to the IN2P3 Science Driver "Study matter-antimatter asymmetry and flavor transitions (flavor)". The *D* coefficient is uniquely sensitive to the imaginary part of the ratio of axial-vector and vector β-decay amplitudes as well as to scalar and tensor interactions. The *D* parameter can provide unique information about the Wilson coefficients of the low energy Effective Field Theory (EFT) of nuclear β-decays. The aim of MORA is a world-leading precision of 10^{-5} on *D*, improving over the currently best limit from neutron decay by one order of magnitude. MORA's particularly novel feature is the in-trap polarization of the ions using lasers. The first phase of this experiment, aiming at a precision of $\sim 10^{-4}$, is being carried out at University of Jyväskylä, Finland. After achieving this goal, the equipment is expected to be moved to the DESIR facility to further improve the precision by a factor of ten.

This experiment uses trapped, laser polarized ions for the precision measurement of the *D* correlation coefficient in a mixed Fermi and Gamow-Teller β-decay transition. Presently ^{23}Mg is the candidate being studied. The proof of principle of the in-trap polarization which combines the high efficiency of ion trapping and of laser orientation is in progress. The detector setup in MORA is similar to emiT **(**but in the latter case a neutron *beam* is polarized). The emiT experiment, which has reached the 10^{-4} level, was limited by statistics, despite the large neutron beam cross-section. Technically the only other *D* correlation experiment was TRINAT (TRIUMF Neutron Atomic Trap). It is sensitive to time reversal violation, and the two experiments are hence complementary.
The project additionally intends to continue measurements with ^{39}Ca at GANIL where beam development has been requested by the proponents. This will not only allow an independent measurement of the *D* parameter but also addresses the Final-State-Interactions (FSI) effect. At this very high level of precision of 10^{-5}, FSI are significant and can be disentangled from new physics contributions thanks to their different dependence on the electron energy.
Presently a few major challenges have been identified to achieve the required precision. These include in particular the large contamination of the beam in the case of ^{23}Mg, which are currently being addressed by the inhouse team at the University of Jyväskylä. The systematic effort to solve this show-stopper looks promising and the incremental steps that are in progress were clearly presented. The problem of contamination for ^{23}Mg will not be a problem at DESIR-GANIL given the availability of a high-resolution spectrometer.

Comments

The scientific council acknowledges the active cooperation of the experimental team with the theorists, such that the best possible interpretations can be made. A detailed account of the found show-stopper is given, demonstrating the knowledge and full control of the present difficulties. However, the overall structure of the project, including the breakdown of the responsibilities and expertise of team members dedicated to this very challenging experiment, is quite unclear. Moreover, a stepwise schedule to reach the final goal needs to be better defined. The scientific council encourages the team to complete the proof of principle polarization measurements and continue the efforts there until the planned competitive limit in precision ($\sim 10^{-4}$) is reached. This is relevant considering that full-fledged experiments with radioactive beams at DESIR will not be possible before 2028 at the earliest. Given the status of the measurement at the present time, the team should be strongly encouraged to discuss with the management of the accelerator at the University of Jyväskylä for securing the large amount of required beam time in a staged way in order to achieve the required precision with ^{23}Mg.
Regarding the next step at DESIR, namely the measurement for ^{39}Ca, a detailed study of the various requirements (procurement of the new lasers, relevant infrastructure for their placement, expert staff, …) need to be done well in advance. Additional financial support needed for the completion of the necessary infrastructure must be consolidated, as presently it does not exist in the approved baseline project. Likewise, the needs at GANIL/SPIRAL2/DESIR should be studied in advance along with the DESIR collaboration and also discussed with the DESIR project team to optimize the relevant technical requirements.

Recommendations

● The scientific council recommends the team to evaluate carefully the possible show-stoppers and to clarify the breakdown structure and plan of the project at the University of Jyväskylä.

● Regarding the next step at DESIR, namely the measurement for ^{39}Ca, the scientific council recommends the realization of a detailed study in a timely manner of the various requirements including the financial aspects, and in coordination with the management of IN2P3.

6. Precision Tests of Fundamental Interactions

6.1 Activities in the n2EDM experiment

Introduction and highlights

Measuring the neutron electric dipole moment (EDM), quasi forbidden in the Standard Model, is searching for CP/T violation in the hadronic sector and is therefore extremely sensitive test of BSM. Current limit can probe new physics at the 10 PeV scale. A neutron EDM measurement is complementary to other ongoing searches of electric dipole moments in nuclei, atoms and molecules.

The work done so far by the LPSC and LPC laboratories within the experiments at PSI is excellent, and the scientific council congratulates the teams for their achievements in developing and delivering experimental equipment but also leading the data analysis of the nEDM and n2EDM projects. All this yielded the currently best limit on the neutron EDM (< 1.8 x 10-26 e.cm), showing clearly the outstanding expertise of the nEDM/n2EDM collaboration.

The new project n2EDM is aiming to improve the current limit by one order of magnitude with 500 days of data taking. The sensitivity of 10^{-27} e.cm will be still statistically limited and relies mainly on the increase of the number of Ultra Cold Neutron (UCN) by a factor 8 (thanks to a larger storage volume and optimized transport of UCN from the source to the apparatus) and on a higher electrical field. IN2P3 contributions, both in terms of personal and financial support, amounts to about 25%; they developed, built and delivered many key elements (vacuum vessel, internal coils, spin analyser, neutron detectors, Hg polarization cell, switch box…) within specifications and schedule. The commissioning of the n2EDM started in 2023 and is ongoing. At present, only the number of stored neutrons seems not to be sufficient (though already now statistical sensitivity compared to nEDM was doubled). The origin of missing UCNs seems to be identified (coating of HV electrodes and isolation rings) and a mitigation strategy is developed by the collaboration aiming to resolve this problem in the near future. Results with test chambers and newly coated electrodes are expected by fall 2024. The current schedule has a two-step approach: a data taking period-up to end 2026 with the aim of reaching 5 x 10^{-27}, followed by a one-year PSI shutdown to increase the UCN intensity by a factor 3 and finally a 3-year data taking up to 2030. Such a schedule aims n2EDM to remain at the forefront of this physics, while the other projects (TRIUMF, ILL) are still under construction.

Recommendations

The collaboration agreement (including common funds) is finishing end 2026 and IN2P3 should secure it up to 2030. The only permanent CNRS staff in the nEDM IN2P3 teams is going to retire soon. To ensure robust operation of the project and to maintain good visibility of IN2P3 in neutron EDM search, the scientific council recommends hiring a CNRS permanent (junior) physicist within the next two years, who is completely dedicated to this field. The scientific council suggests to investigate the possibility to fill such a position through a joint position with other CNRS institutes satisfying the interdisciplinary demands of this project. Such a reinforcement of the teams is essential to strategically prepare for future projects.

6.2 The GBAR project

Introduction and highlights

The GBAR (**G**ravitational **B**ehavior of **A**ntihydrogen at **R**est) project, AD-7 experiment, is a multinational collaboration at the Antiproton Decelerator (AD) at CERN. It aims to measure the free-fall acceleration of ultra-cold neutral anti-hydrogen atoms in the terrestrial gravitational field and to compare it with acceleration of normal hydrogen. The experiment offers a unique opportunity to probe fundamental interactions of antimatter in the context of general relativity. This initiative is crucial for verifying the Weak Equivalence Principle (WEP) with antimatter, potentially providing answers to unresolved questions about dark matter and dark energy. Proposed to CERN's SPSC in 2011, GBAR was accepted by the Research Board in 2012 and commenced installation in 2017, joining two other experiments at CERN's AD facility devoted to measuring the free fall of antihydrogen (AEgIS and ALPHA). GBAR was the first AD experiment to receive a beam from the newly installed ELENA decelerating synchrotron in 2018.

The GBAR experiment consists of preparing anti-hydrogen ions (one antiproton and two positrons) and sympathetically cooling them with a laser-cooled co-trapped beryllium Be+ ion cloud to less than 10 μK (roughly m/s velocity). The ultra-cold ions are then photoionized using a laser pulse that removes the outermost positron and forms neutral anti-hydrogen. The free-fall time of these atoms over a known distance is then measured inside a detection chamber. In addition to the antiprotons from the AD, GBAR needs a constant flux of positrons. For this, a small accelerator with a tungsten target is used. An electron beam of 10 MeV strikes this target, and positrons are collected by using a magnetic separator to filter out electrons and the gamma-ray background. These positrons are then trapped with a Penning–Malmberg trap. The GBAR experiment features a pioneering electrostatic decelerator concept for antiprotons that avoids the losses inherent in the foil technique used by the other experiments.

GBAR achieved a first major milestone in 2022 with the production of antihydrogen, joining an elite club. The production scheme is being optimized for 2024 measurements of production cross sections and the Lamb shift of antihydrogen to access the antiproton radius. The longer term (post-LS3) plans will be directed to the production of antihydrogen ions and a free-fall measurement to surpass 1% precision.

The collaboration currently comprises 62 publishing authors from 20 institutes and 9 countries, with an important contribution from the French institutes IN2P3, INP, ILL and IRFU (the GBAR spokesperson, Patrice Pérez, is affiliated with IRFU).

The experiment stands out from the competing experiments (Alpha, Asacusa, AEgIS) with several technical and methodological innovations. The most notable is the cooling of the antihydrogen ion to extremely low temperatures (around ten micro-Kelvin for GBAR compared to 500 milli-Kelvin in Alpha-g) through Coulomb interaction with co-trapped beryllium ions cooled by laser. Moreover, the atoms are not subject to magnetic fields in GBAR. This technique has the potential for a ppm-level measurement of the free-fall of antimatter, compared to the ~30% precision of the Alpha-g measurement. This is particularly important in the context of the current Alpha-g experimental results showing disagreement with simulations, leading to the necessity of a complementary experiment with different and lower systematic uncertainties.

The project also uses a unique electrostatic decelerator for antiprotons, avoiding the losses inherent to the foil technique used by other experiments. This innovation, developed by IN2P3, has been adopted by other similar projects, demonstrating its effectiveness and importance.

The principal scientific return – a precision measurement of antimatter gravity – is not expected before the end of the next LHC long shutdown in 2028. Before this shutdown (i.e. in 2026), GBAR plans for intermediate, but important, measurements, such as the Lamb shift of anti-Hydrogen (which is in itself a test of matter/anti-matter symmetries), and the cross-section for anti-hydrogen ion exchange.

The teams involved in the project have excellent technical and scientific expertise. They have the capacity to carry out the planned program, even if significant progress remains to be made on the production rate of antihydrogen atoms and on the sympathetic cooling stage, defined in principle, but not yet implemented. The production and cooling of antihydrogen ions require a high density of positrons, which represents a technical difficulty. Continued optimization of experimental conditions to maximize antihydrogen production and minimize losses is essential to achieve the project's objectives. These technical and logistical challenges require close coordination between the different teams and partners, which needs to be articulated (particularly the CNRS/CEA links: INP, IN2P3, IRFU), as well as prioritization among the many but different objectives for 2024-2025: Penning trap for antiprotons, Lamb shift measurement on antihydrogen, improvement of positron transport, study of the formation process via the “anti” scheme using protons, etc.

The IN2P3 team consists of one permanent researcher from IJCLAB and (on average) one PhD student or one postdoctoral researcher (PD). The contributions of IN2P3, notably the development of the electrostatic decelerator and the coordination (the future of which needs to be clarified) of antihydrogen production efforts, are crucial for the success of the project. These activities offer visibility to IN2P3 within the scientific community. IN2P3 also plays a key role in the training of researchers. Theses and doctoral projects supervised by IN2P3 researchers have produced significant results and contributed to the necessary presence at CERN to carry out the experiment. Because of its size, the IN2P3 presence at CERN is limited in terms of total FTE, but is nevertheless important relative to the contribution of all other teams, in a context where the lack of person power on site impacts the rapidity of progress of the experiment.

Comments

The goal of GBAR is to test the WEP with antimatter and is clearly connected to IN2P3 science drivers. France has been a pillar of the experiment since its beginning with CEA, LKB, IPCMS, and IJCLAB. IN2P3 provided key and well recognized contributions, notably the deceleration of the antiproton beam, thanks in particular to the work of 5 PDs and 4 PhD students. The sympathetic cooling of anti-H ions is one of the few techniques with the potential to reach the ppm precision needed to search for possible WEP violations. In addition, the project is pursuing important intermediate science goals, such as the measurement of the antiproton charge radius via the Lamb shift and a measurement of anti-H and anti-H ion production cross-sections. The timely success of the experiment requires a stronger presence at CERN and reinforced technical coordination of the French efforts, in particular addressing the positron transport beamline efficiency and the construction and test of the free fall chamber. To ensure the further success of this important program, the question of person power is crucial. The support by supplementary person power (e.g., PDs) with potential for presence at CERN over extended periods is recommended, and possible solutions could be explored via links with INP. However, before taking any decision, the question of the long-term personal investment of the PI must be clarified.

Recommendations

● The scientific council recommends to clarify the long-term personal investment of the PI, before supporting the necessary supplementary person power at CERN over extended periods.

6.3 The COMET experiment

Introduction and highlights

The observation of neutrino oscillations implies that neutrinos are massive, and that individual lepton flavors are not conserved. This contradicts the original SM formulation, in which neutrinos are massless by construction, and an accidental symmetry leads to the conservation of total and individual lepton numbers. However, lepton flavor-violating muon decays are extremely suppressed in the SM even when neutrino oscillation effects are taken into account. In particular, the branching ratio of $\mu \rightarrow e\gamma$ is calculated to be of the order of 10^{-54} due to the huge reduction factor of $(\Delta m_{ij}^2 / M_W^2)$ where Δm_{ij}^2 is the squared-mass differences between neutrinos of flavor i and j, and M_W is the W-boson mass. The current limit on the probability of the $\mu \rightarrow e$ transition is 7×10^{-13} and it was set in 2006 by the SINDRUM-II experiment at PSI. The COMET experiment at J-PARC plans to study the $\mu \rightarrow e$ transitions in the field of a nucleus, and will operate in two phases. The Single Event Sensitivity (SES) is expected to improve by a factor of ~100 the current best limit with Phase-I, and by a further factor of ~100 with Phase-II, thus reaching a SES of the order of 10^{-15} and 10^{-17}, respectively. The ambitious goal of the COMET experiment should be achieved by realizing a high-quality pulsed beam and an unprecedentedly powerful muon source together with an excellent detector apparatus that should tolerate a severe radiation environment. Muons, as the decay product of negatively charged pions produced in backscattering collisions of a 3.2 kW 8 GeV pulsed proton beam hitting a graphite target, are efficiently delivered through a curved transport solenoid (TS). This dedicated beam line is currently in construction at J-PARC. At the exit of the 90° bending angle transport solenoid, muons are directed to a stopping target surrounded by the COMET detector. Aluminum is a very good material candidate for the manufacturing of the stopping target. The main components of the COMET detector for Phase-I consist of a cylindrical drift chamber (CDC) and a cylindrical trigger hodoscope (CTH). The CDC has a length of ~1.6 m and a diameter of ~1.7 m. It allows the measurement of 105.6 MeV electrons emerging from the $\mu \rightarrow e$ transitions with a resolution of 0.2%.

The signal signature for ^{27}Al nuclei is the detection of 104.97 MeV electrons. The background to this process can be divided into three classes: beam-related background, physics background, and cosmic rays. While the former can be strongly reduced thanks to the use of pulsed proton beams, the latter should be reduced by using a cosmic ray veto system (CRV) placed around the COMET detector. This system should be able to recognize, and hence veto, cosmic rays with an inefficiency of 10^{-4} (the inverse of this quantity, 10^4, is also called suppression factor). The plan of the COMET Collaboration is to build the CRV using layers of plastic scintillators and bakelite 1.4 mm gap Resistive Plate Chambers (RPC). With a 10^4-suppression factor, current simulations predict for COMET Phase-I less than 0.3 events of cosmic rays, which appears to be still by far the largest expected background contribution. Therefore, the accurate design and realization of an excellent CRV is mandatory for the success of this experiment.

In Phase-II, the beam power is increased to 56 kW. The TS is extended to the full 180◦ bend, and the Electron Spectrometer Solenoid (ES) will be constructed. The ES is a 180◦ bend curved solenoid and it will select the charge and momentum of the emitted electrons. Neutral particles cannot directly reach the detector section in Phase-II. This upgrade will help decrease the hit rate of the downstream detectors.

Comments

The COMET's physics program provides excellent complementarity to other charged lepton flavor violation experiments. The observation of a neutrinoless transition would be incontrovertible evidence for physics beyond the SM, and the most important particle physics result in decades. Conversely, the absence of an observation would still provide valuable constraints on models of physics beyond the SM. As mentioned previously, during Phase-II Single Event Sensitivity is expected to be 10000 times lower than the current limit and comparable to what is expected for the Mu2e experiment. Phase-II is thus expected to be both crucial for the COMET collaboration and an important goal for the French contribution.

The French community contributing to COMET is relatively small (around 5 Full Time Equivalent physicists). Nevertheless, it presents important commitments, appropriate to the size of the group, including support in computation through the IN2P3 Computing Center, data analysis, and construction. From the data analysis point of view, the French group proposed an alternative promising track reconstruction program using the cylindrical drift chamber, based on the Appolonius' Problem with a plan to include Graph Neural Network methods in the future. If this is adopted by the experiment as the main tracking algorithm, it will be of considerable impact. From the construction point of view, the French group is developing part of the Cosmic Ray Veto with Resistive Plate Chambers, in order to reduce what is expected to be the main background of this experiment. COMET uses simulation tools also developed by the French group. Those activities ensure a very clear visibility and impact on the experiment.

Using the aforementioned innovative tool for the atmospheric muon simulation, the French group demonstrated that the amount of cosmic ray background is larger than first preliminary expectations, which motivates the reinforcement of the Cosmic Muon Veto. In this perspective, the French COMET community had considered initially using Glass Resistive Plate Chambers (GRPCs). However, being unable to produce GRPCs in time for Phase-I due to shortage of person power following the pandemic, the group found a plausible alternative option with bakelite RPCs, for which the group has already established a collaboration with the CMS Korea group, responsible of the CMC RPC system upgrade. While this solution seems viable and efficient, there are still open questions concerning their rejection power in very particular radiation conditions, depending on a yet-to-be designed shielding, their funding, their final design, and the construction timescale.

Recommendations

Following what has been reported, and taking into account the assessment received from the external reviewers, the scientific council strongly recommends supporting the French groups involved in the COMET experiment at J-PARC. In particular, if it is decided to move forward with the proposed CRV development, a postdoc should be granted and will join the installation of the RPC detector. Moreover, it is recommended to make sure that one mechanical engineer contributes to the commissioning and installation on site. This will also allow the consolidation of the IN2P3 group for the more challenging and powerful Phase-II of the experiment.

The support expressed above should be understood considering the following important points:

- The urgent finalization of the Cosmic Ray Veto system design, given the importance of this detector to the success of the experiment. This system, made of a combination of two independent subsystems based on plastic scintillators and bakelite, double gap RPC, respectively, must be defined in all details. The aggressive suppression factor required (SF~10^4) does require an overall redundant system with high single-plan efficiency, while keeping low probability of vetoing fake cosmic-ray events. A particular attention should be paid to the RPC system (including the front-end electronics which would be based on the CMS model), that would be an IN2P3 responsibility.
- The urgent finalization of the particle fluences and rates calculation expected in the detector area, including the effects of the shielding system, needed to reduce them to an acceptable level and to ensure safe operation of the CRV.
- More generally, it is also very important to finalize the organization of the project of the French groups, assigning clear tasks, defining responsibilities and milestones, making sure that all relevant activity areas are sufficiently covered.
- The expansion within the group of the knowledge and use of the programming language *Julia*. While this language is very suitable for offline tracking, it is also poorly known in the community. It is important to make sure that the COMET group in charge of the event reconstruction takes the responsibility of propagating this know-how to more people in the group.