Symmetries and Fundamental Interactions – WG5

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1. Introduction

The presently known fundamental interactions governing Nature and the Universe from the largest to the smallest distances display symmetries and symmetry breaking. Noether's theorem links symmetries with conservation laws which depend on the interaction type. It is well known that, for example, conservation of momentum and angular momentum rest on isotropy of space and the invariance of the laws of physics under translational and rotational transformations. On the other hand, for various apparently conserved quantities like lepton number an underlying symmetry is absent or yet unknown, motivating theoretical developments and experimental searches.

Four fundamental interactions: electromagnetic, weak, strong and gravitational, are well identified. The first three have been successfully included in the Standard Model (SM) of particle physics while gravity has so far resisted all attempts to be cast into a viable quantum field theory together with the other interactions. We know a set of basic constituents, leptons, quarks and gauge bosons, which form all known matter and the interactions between them as described by the SM. The recent discovery of the Higgs boson has in many ways completed the SM.

Nuclear Physics has played a major role in finding and establishing the laws which govern the physics at the most fundamental level. One of the most notable examples is the maximal violation of spatial inversion symmetry, parity *P*, in the weak interaction. Shortly after the discovery of *P* violation also the combined *CP* symmetry (*P* and charge conjugation *C*) was found to be broken. These discoveries have triggered intense research on symmetry violations, including those of time reversal (*T*) symmetry. In Quantum Field Theory (QFT) *C*, *P*, and *T* are related by the *CPT* invariance theorem resting among other assumptions on Lorentz Invariance (LI).

Today, fundamental physics is located interdisciplinary between nuclear, atomic, particle and astrophysics. Major advances in the state-of-the-art technology have made novel approaches feasible. The most accurate technologies from various research fields are employed to prepare the fundamental systems under study. They range from low-energy particles, ultracold atoms, ions and molecules (with major applications also in chemistry, quantum information processing and metrology), through novel sensors and radiation detectors (also used for medical applications), to the analysis of complex sets of data and extracting the underlying information (e.g. big data, computing, pattern recognition, ...). At the same time the most advanced theoretical and calculational techniques are developed and applied by nuclear, atomic and particle theory to perform ever more stringent comparisons between theory and observation, and to establish discrepancies. While nuclear and particle physics have developed along different pathways, technologies have usually been shared. We find today, in particular also from high energy particle physics, an increasing interest in complementary approaches to the same most fundamental questions and a growing appreciation for key experiments in the intensity and precision physics domain (see Box 'Precision Challenge') sometimes sensitive to high energy and mass scales exceeding those for the present and future collider experiments. Nuclear physics and its technologies play crucial roles in many such experiments. Theory is about to develop common languages, for example in the form of the Standard Model Effective Field Theory (SMEFT), which can systematically parametrize any new physics at high energy scales and connect experiments at different lower scales. But precision physics does not stop there and also most sensitively probes the realm of new physics at low mass scales with very small couplings as, for example, in the case of axion-like particles (ALPs). The underlying theme is to find new particles, interactions, and symmetries or symmetry violations which could help overcoming the shortcomings of our present understanding and which could give signs for physics beyond the SM. Along this path, many experiments also aim at testing some of the most basic assumptions of our theories today, in particular LI, *CPT* symmetry and permutation symmetry connected to the spin-statistics theorem (SST).

Quantitative understanding of measurements at the highest levels of precision and accuracy is a necessary key ingredient for a more complete description and understanding of Nature. The research in the field proceeds along two main routes: precision determinations of fundamental parameters and searches for deviations from the SM predictions. Precision measurements of, for example, masses, mixings and coupling constants are ideally carried out in complementary approaches to allow overdetermination of theory parameters and cross-checks. With improved experimental precision, sensitivity and stability, long-duration observations can be turned into searches and tackle the question of time dependence of fundamental “constants”, the constancy of which is often taken for granted. Another class of sensitive searches can be performed where the predicted value of an observable is negligibly small or even zero in the standard theory. Examples include permanent electric dipole moments (EDM) of particles, neutrinoless double beta ($0\nu\beta\beta$) decay or charged-lepton flavour violation (cLFV), so that verified experimental signals translate into discoveries.

Despite the tremendous and highly encouraging success of the present SM, various observations point to the need for its extensions. The above mentioned difficulty to include gravity is one example. A number of observations, astrophysical and astronomical, pose enormous challenges, such as the likely existence of Dark Matter, accelerating expansion of the Universe, and Baryon Asymmetry of the Universe (BAU) with matter by far outnumbering antimatter. Observations call for baryon number *B* violation, connected or not to lepton number *L* violation, and additional *CP* violation which is not found to be sufficiently strong in the SM although sufficiently strong CP violation is readily obtained in many of its extensions. Search experiments involve the full spectrum of particles from neutrinos, charged leptons to hadrons to stable and radioactive ions, and molecules. It is important to recall that *CP* violation naturally appears in quantum chromo-dynamics but must be unnaturally small as proven by the absence of finite values of permanent hadronic EDM at least at the level of sensitivity obtained experimentally so far. Also improved *B* and *L* violation searches push the limits and continue to provide some of the most stringent bounds on models of new physics.

This report on “Symmetries and Fundamental Interactions” presents a short overview and status of the vibrant research activities and discusses the prospects and most promising new directions, especially for the European research landscape with its present and future facilities.

Precision Challenge

Studies of symmetries and in particular observation of symmetry violations (“symmetry breaking”) rely on precision measurements of physical observables and require ingenious experimental conditions and hardware and an unambiguous description of the underlying physics: celebrated examples are the discoveries of parity (*P*) and charge-parity (*CP*) violation over 50 years ago, which were largely unexpected and fundamentally changed our understanding of Nature.

Precision experiments often demand high statistics, long measurement time and utmost control of experimental parameters. Improvements are usually achieved in iterations, where a next-generation set-up exploits the experience from previous measurements in an attempt to overcome limitations or shortcomings of the previous versions by developing novel approaches. It is also beneficial to perform independent measurements of the same physical quantity in diverse systems or with different experimental devices – leading to varying systematic errors – in order to scrutinize the validity of the results. Eventually a robust theoretical model is required for the interpretation of the outcome or the determination of its significance. Recently, the Standard Model Effective Field Theory is receiving more attention as a model-independent approach allowing the systematic intercomparison of many experiments (see Box ‘Standard Model Effective Field Theory’). The interplay between experiment and theory stimulates the development of both theoretical concepts or models and of (beyond) state-of-the-art instrumentation.

In our quest to better understand the structure of matter and fundamental interactions, the *precision frontier* is complementary to ever higher energy and intensity experiments and is a promising strategy towards new discoveries.

2. SM parameters

2.1 Leptons

There are only a few parameters which characterize leptons, i.e. masses, mixing angles, lifetimes, charges and magnetic moments. As spin 1/2 particles they do not possess higher-order electromagnetic moments. It is an observational fact that the value of the charge is quantized ±*e*, or 0, which is far from being understood. Open issues include the difference in mass scales between charged and neutral leptons, and the specific structure of the neutrino mass matrix which is investigated in neutrino oscillation experiments.

2.1.1 Neutrinos

More than a dozen experiments with atmospheric, solar, accelerator and reactor neutrinos have clearly proven that neutrinos from one flavour, e.g. an electron neutrino ν_e from the nuclear fusion in the core of the sun, change into another neutrino flavour, e.g. a muon ν_μ or tau neutrino ν_τ, in-flight. This requires neutrinos to have non-zero masses and to exhibit a non-trivial mixing between neutrino mass states ν_1, ν_2 and ν_3 and neutrino flavour states ν_e, ν_μ and ν_τ. This discovery of neutrino oscillations opened the door to the studies of the neutrino properties which are very important for nuclear and particle physics, as well as for astrophysics and cosmology. Unfortunately, neutrino-oscillation experiments are not sensitive to neutrino masses but to the differences of squared neutrino masses Δm^2_{ij} (i,j=1,2,3) and to the parameters $U_{\alpha i}$ (α = e, μ, τ) of the mixing matrix. Currently we know Δm^2_{21} and the mixing angle θ_{12} from solar and reactor neutrino experiments, $|\Delta m^2_{32}|$ and θ_{23} from atmospheric and accelerator neutrino experiments, and the 3rd mixing angle θ_{13}, determined mainly by reactor neutrino experiments (Daya Bay, RENO, Double Chooz).

An important question – in particular to explain the smallness of the neutrino masses – is the mechanism for neutrino-mass generation. Neutrino masses are at least six orders of magnitude smaller than the masses of the other fundamental fermions. Therefore we expect that there might be something beyond the usual Yukawa coupling to the Higgs, and thus physics beyond the SM, required to explain the tiny neutrino masses, for example via the so-called see-saw mechanism. A missing experimental result in this respect is the mass hierarchy: depending on the sign of Δm^2_{32}, or Δm^2_{31}, respectively, $m_3 := m(\nu_3)$ is the largest or the smallest of all neutrino masses (see Fig. 1). This hierarchy will be determined with accelerator or reactor neutrinos in long-baseline experiments or with atmospheric neutrinos using neutrino telescopes.

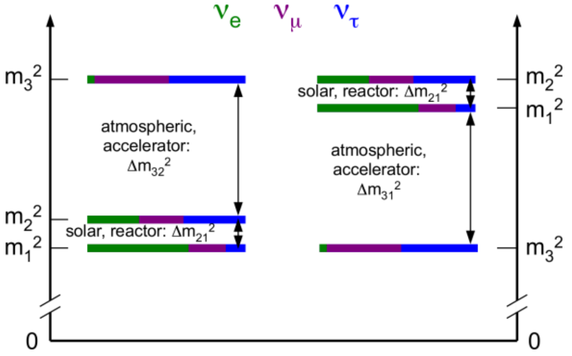

Figure 1: Possible hierarchies of neutrino masses: normal (left) and inverted (right) hierarchy.

Neutrinos are believed to outnumber atoms in the Universe by nine orders of magnitude. Therefore, even tiny neutrino masses contribute to the Dark Matter as Hot Dark Matter component and influence the evolution of the Universe. The direct determination of the neutrino mass scale by the study of the kinematics of weak decays is usually pursued by investigating the endpoint region of the tritium beta-decay spectrum (KATRIN). Recently the successes of cryobolometer and magnetic microcalorimeter techniques drew attention to the electromagnetic deexcitation spectrum after ^{163}Ho electron capture (ECHo, HOLMES, NUMECS). These direct searches for the neutrino mass scale in the sub-eV range are complementary to cosmological analyses and searches for $0\nu\beta\beta$ decays.

In contrast to all other fundamental fermions, neutrinos are neutral. Thus they could be their own antiparticles (Majorana neutrinos) violating *L* conservation. Nearly all neutrino mass models beyond the SM require Majorana neutrinos and no symmetry is known related to *L* conservation. The search for $0\nu\beta\beta$ decay is a sensitive test for *L* violation. A positive signal would definitively be related to new physics which could be explained by neutrinos being Majorana particles or by some other *L* violating effects. The second-order weak $0\nu\beta\beta$ transition can occur without neutrino emission if neutrinos are their own antiparticles. The transition rate is sensitive to the weighted sum of all neutrino mass states contributing to the electron neutrino, complementary to the observable mass in direct beta-decay searches. Unfortunately, in addition to unknown Majorana phases of the neutrino mixing matrix and the unknown neutrino hierarchy, the calculation of the nuclear matrix elements still introduces significant uncertainties to this way of determining the neutrino mass scale. Currently, half-life sensitivities of 10^{26} y for $0\nu\beta\beta$ decay are under investigation requiring ultra-clean, 100 kg-scale isotope-enriched detectors. In Europe, major efforts are under way with installations in the underground laboratories of Gran Sasso, Modane and Canfranc. The Majorana nature of neutrinos, together with heavy right-handed neutrinos predicted in most neutrino-mass theories beyond the SM and with leptonic *CP* violation, can provide via leptogenesis the sought-after source for BAU.

The SM describes three flavour and three mass states of neutrinos. There are several hints (e.g. the so-called “reactor anomaly”) that there could possibly be a forth, sterile neutrino state, which does not couple to W- or Z-bosons. With short-baseline neutrino-oscillation experiments or with precision studies of the endpoint spectra of tritium beta decay or ^{163}Ho electron capture the existence of light sterile neutrinos will be checked. Sterile neutrinos with keV masses are an interesting candidate for Warm Dark Matter.

2.1.2 Charged leptons and fundamental constants

Properties like masses and magnetic moments of free and bound charged leptons are measured in precision experiments and also used in determinations of additional fundamental constants. Consistency of independent results provides further tests of fundamental theories. Some dimensionless constants, such as the fine structure constant α or the proton-to-electron mass ratio, are of particular interest.

Since the original calculations of Bethe, Feynman and others of the hydrogen Lamb shift, quantum electrodynamics (QED) calculations of a number of observables have advanced to the point where uncertainties of fundamental constants, or contributions from the strong interactions through hadronic vacuum polarization, or hadronic light-by-light scattering limit theoretical accuracy.

The Rydberg constant R_∞ is the most precisely determined fundamental constant; it links the fine structure constant, the Planck constant, and the electron mass. Because it is currently measured only in H and D, its value is nearly 100% correlated with the proton and deuteron charge radii. Because of the proton radius discrepancy between muonic and electronic determinations (see below), the value of R_∞ is currently under debate. In near future, laser spectroscopy of other calculable systems, such as helium ions, can provide independent determinations of R_∞, when combined with the respective nuclear radii and polarizabilities.

The magnetic moment anomaly $(g_\mu\text{-}2)/2$ of the muon has been measured with $5\text{x}10^{-7}$ precision at BNL and a 3-4σ discrepancy with the calculated SM value persists (see box in WG1). A new experiment with a five-fold improved precision on g_μ-2 will start data taking at FNAL soon. Another g_μ-2 project is being pursued at J-PARC. Since the muon is 200 times heavier than the electron, its anomaly is intrinsically much more sensitive to hadronic corrections and to the existence of as yet unknown hypothetical heavier particles.

Comparison of measurements with SM calculations for the magnetic moment or *g*-factor of the free and the bound electron in hydrogen-like systems provides the most stringent consistency tests of QED. Therefore, the determinations of *g*-factors (see Fig. 2) will be continued at high-precision levels with the potential to discover new physics. The fine structure constant α determines the strength of the electromagnetic interaction. It enters as an expansion parameter in QED. An example is the magnetic moment of the electron which permits the present best determination of α at the 10^{-10} level based on the g_e-2 measurement of a single electron in a Penning trap at Harvard and QED calculations performed up to the α^5 order. The most accurate value of the electron mass m_e (in amu) with a relative precision at the 10^{-11} level is obtained by a comparison of state-of-the-art bound-state QED calculations and precise measurements of the *g*-factor of the bound electron in $^{12}C^{5+}$ at Mainz. Furthermore, the superb precision achieved in these recent experiments makes them sensitive to hypothetical particles, complementary to the muon *g*-factor. Of course, a strong theoretical effort and thorough scrutiny is required.

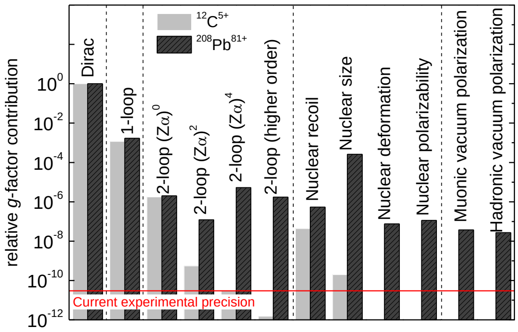

Figure 2. Magnitudes of the relevant theoretical contributions to the bound electron g-factor in $^{12}C^{5+}$ and $^{208}Pb^{81+}$: The leading Dirac contribution, one- and two-loop bound-state-QED corrections, nuclear and muonic effects. The present experimentally achieved precision in $^{12}C^{5+}$ is indicated with the red line. A similar precision should be reached for Pb.

Bound-state QED in the strong-field regime ($Z\alpha$ close to unity with Z being the nuclear charge) is explored by x-ray spectroscopy for Lamb-shift measurements, by laser spectroscopy of hyperfine and fine structure, and by microwave spectroscopy of magnetic substates for bound-electron *g*-factor determinations. A careful comparison of results from ions in different charge states (H-, Li-, B-like) would allow for disentangling nuclear structure and QED effects to a high degree. The highest accuracy is reached with cooled highly charged ions stored in precision traps from electron beam ion trap (EBIT) sources or accelerator facilities like the ESR storage ring at GSI with subsequent deceleration such as proposed for HITRAP. Experiments in storage rings (CRYRING, ESR, HESR and SIS100 at GSI/FAIR) offer wide Doppler tunability and therefore access to laser spectroscopy on heavy highly charged ions, in particular, when combined with novel XUV laser sources.

Another well-established phenomenon in strong-field QED is electron-positron-pair creation during scattering of two nuclei. When the total charge Z' exceeds the supercritical value Z' ≥ 173, the system enters the unperturbative QED regime, which should lead to, among other phenomena, a significant enhancement of pair creation. This enhancement has not yet been observed and requires further investigation.

Precision spectroscopy of the 1S-2S transition and the ground-state hyperfine splitting (HFS) of muonium determines the mass and the magnetic moment of the muon, impacting the determination of g_μ-2 and providing an independent QED test, possible access to the fine structure constant, the Rydberg constant and various SM tests, such as that of charge equality between the two lepton generations. Efforts are ongoing to perform a new HFS experiment at J-PARC aiming at an improvement in relative precision from $1.2\text{x}10^{-8}$ to 10^{-9} and a new 1S-2S measurement at PSI to improve from $4\text{x}10^{-10}$ to 10^{-11}.

Further, stringent QED tests are performed with positronium. The spectroscopy of the 1S-2S transition is under way in several projects worldwide. They aim at improving the relative precision to 10^{-10}. The possibility of another two orders of magnitude would permit an independent determination of the Rydberg constant. A determination of the 2S HFS aims at 10^{-5} or better in order to shed light on the current discrepancy of 3.6σ between the most precise measurements and bound-state QED calculations for this system. Considerable effort will be needed on the theoretical side in order to obtain the adequate accuracies.

The weak coupling constant G_F has been determined with $5\cdot10^{-7}$ precision from a 10^{-6} measurement of the lifetime of positive muons by the MuLAN collaboration at PSI together with two-loop QED calculations and including electron mass corrections. The muon lifetime is the most precisely measured lifetime of any particle or state. The electroweak sector of the SM is determined by G_F, the fine structure constant α and the Z-boson mass. It is a cornerstone in weak-interaction physics and tests lepton universality even in semi-leptonic decays, including nuclear beta decay. The extraction of G_F from experimental data assumed the validity of the SM. Planned weak-interaction studies and searches for new physics beyond the SM using neutron and nuclear decays which aim at a 10^{-4} precision must take into account that the model-independent determination of the weak coupling from muon decay is less constrained, down to only about $3.6\cdot10^{-4}$.

2.2 Baryons

Precise measurements of baryon properties provide relevant information on fundamental interactions. On the one hand, precise measurements in nuclear β decays enable probing the structure of the weak interaction. At a high-precision level, electromagnetic and strong interaction effects have to be considered. On the other hand, precise measurements of certain nuclear parameters permit improving QED tests and determining fundamental constants in a way largely unaffected by nuclear-structure uncertainties.

2.2.1 Semileptonic decays

In a general description of nuclear and neutron β decay, the decay probability can be written as a function of the spin of the parent, the momenta of the electron (positron) and (anti)neutrino and the spin of the electron (positron). It contains observable correlations and parameters, e.g., the electron-neutrino momentum correlation *a*, the Fierz parameter *b* influencing the electron spectral shape, the beta-asymmetry parameter *A* between nuclear polarization and electron momentum, and the neutrino-asymmetry parameter *B*. Also triple correlations are being studied, especially the time reversal violating correlations between nuclear spin, electron and neutrino momentum (*D*) or nuclear spin, electron momentum and spin (*R*). In practice, the neutrino momentum cannot be measured. It is therefore necessary to measure the recoil momentum of the nucleus to determine the full correlations.

The accuracy of measurements is often hampered by the low kinetic energies of the recoiling nucleus. In the study of nuclear decays, major progress has been achieved recently by using atom and ion traps to store the radioactive nuclei in vacuum, allowing one to accurately measure the direction and energy of the recoil. The correlation coefficients, *a* through *R*, depend on coupling constants and nuclear matrix elements. For pure Fermi or Gamow-Teller β transitions these coefficients are independent of the matrix elements and thus, to first order, of nuclear-structure effects; they depend only on the spins of the initial and final states. The description of β decay, and of the weak interaction in general, in terms of exclusively vector (V) and axial-vector (A) interactions, i.e. the V-A theory as low-energy effective part of the SM, found its origin in measurements of the beta-neutrino correlation coefficient *a*. The discovery of parity violation was made from the observation that the beta-asymmetry correlation coefficient *A* is non-zero. In general, choosing the appropriate initial and final states in Fermi and Gamow-Teller β transitions and accordingly selecting the correlation coefficients, one can either accurately measure the g_A/g_V coupling-constant ratio or search for symmetry violations or yet undiscovered scalar (S) and tensor (T) contributions. Such searches are now under way at laboratories around the world, aided by the advent of new high-intensity sources of cold and ultracold neutrons and by the ability to trap significant numbers of radioactive atoms or nuclei.

For neutrons, many landmark results have been obtained at the ILL which today provides the world's highest intensity cold neutron beams. A new type of beam-station for the measurement of neutron decay angular

Standard Model Effective Field Theory

In recent years, an overarching framework has been developed for searches for new physics: the Standard Model Effective Field Theory (SMEFT). It can be used to put model-independent limits on coupling constants that parametrize physics beyond the SM and to correlate experimental data for different processes. As such, it provides a fruitful meeting ground of experiment and theory. In particular, the SMEFT has become a tool of choice for the analysis of high-precision searches for symmetry-breaking observables at low energy as well as for studies of new physics at colliders. Its basic idea is the following: In searches for new physics assumed to originate from a yet unknown fundamental theory at some high-energy scale Λ, the SM should be regarded as an *effective* field theory, which is valid up to an energy scale of about Λ /10. In natural units, ħ=c=1, the action is dimensionless, and therefore the Lagrangian density has mass-dimension four. The SM contains only renormalizable operators of mass-dimension two and four. The effects of new physics can then at low energy be described model-independently with an effective Lagrangian density of the form

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \cdots$$

where $\mathcal{L}^{(4+k)}$ contains all possible operators of dimension 4+*k* made up of the SM fields. New physics gives rise to higher-dimensional operators, suppressed by powers of the high-energy scale Λ. Any fundamental quantum field theory at high energy, when systematically expanded in inverse powers of Λ, results in such an effective field theory at lower energy, with specific values of the coefficients that multiply the higher-dimensional operators. Remarkably, only one dimension-five operator exists, which, after electroweak-symmetry breaking, leads to a Majorana mass for the neutrinos. There are, however, many dimension-six operators in $\mathcal{L}^{(6)}$, but often only a very limited number contribute to specific low-energy observables. As an example, a dimension-six operator would shift the anomalous magnetic moment of the electron by an amount of order $O(m_e^2/\Lambda^2)$. The agreement of experiment with QED calculations translates into a lower bound on Λ of order 10 TeV, implying that QED is valid to this energy scale at least. Dimension-six operators have been studied in, for instance, neutron and nuclear beta decay, hadronic and atomic electric dipole moments, and lepton-flavor violating processes.

correlations, called proton and electron radiation channel (PERC) is under construction at FRM II and a successor installation is under discussion for a fundamental-physics beamline at the ESS. Detailed calculations show that the spectra and angular distributions are expected to be distortion- and background-free on the level of 10^{-4}.

Angular correlations of momenta and spins of particles emitted in semileptonic decays of elementary particles and nuclei allow for direct searches for beyond SM phenomena as all observables (correlation coefficients) depend explicitly on the exotic interactions. The sensitivity to these interactions varies from one transition to another and between correlation coefficients so that the best constraints are obtained in combined analyses including those of pion, neutron and nuclear decays. Recently the model-independent SMEFT approach has been used to analyze such processes (see Box 'Standard Model Effective Field Theory'). Typical experimental sensitivities at the 10^{-3} level give access to energy scales of a few TeV for beyond SM physics complementary to collider searches. Present experimental accuracies of the correlation coefficients in semileptonic decays are at the level of 10^{-2} – 10^{-4}. Efforts are ongoing to improve these accuracies by an order of magnitude. Soon a large number of such results will become available as major efforts are under way in Europe and North America. Precise values for the electron-neutrino correlation $a_{\beta\nu}$, the Fierz parameter b_n, the beta-asymmetry parameter A_β, and the neutrino-asymmetry parameter B_ν are expected. The correlations involving the electron spin are highly attractive, especially because of their linear dependence on the small exotic couplings. However, so far they remain largely unexplored because of experimental difficulties. This could change in the future with the newly proposed BRAND experiment to measure simultaneously seven electron-spin-dependent correlations in neutron decay. The ideal facility for this novel approach will be the fundamental-physics cold-neutron beamline at the upcoming ESS. Besides with the neutron, *b* will be measured via the shape of nuclear β spectra. The main idea in existing projects is the confinement of the source inside the electron-detection setup to avoid systematic effects related to electron scattering. Nevertheless, improvements in β-decay detection and simulations are mandatory to reach a precision level below 0.5% on *b*. The quadratic dependence of the β–ν correlation coefficient *a* in exotic couplings implies that, to remain competitive with LHC, a precision level of 10^{-3} or better should be reached. Addressing this challenge requires experimental devices with advanced control of systematic effects, a goal being pursued in several projects. Depending on the availability of long beam periods at dedicated facilities like ISOL@Myrrha and building on the advances in experimental techniques, more projects might be developed in Europe. On the theoretical side, the consideration of radiative and recoil corrections is mandatory. At this level of precision, experiments also become sensitive to strong-interaction effects. For instance, the β-spectrum shape depends on a weak-magnetism term whose magnitude is poorly known, especially for nuclei with mass numbers larger than 40, where a large component could be responsible for the already mentioned reactor neutrino anomaly.

2.2.2 Quark mixing matrix

It is well established that the quark weak-interaction eigenstates are mixtures of their mass eigenstates, described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The unitarity of this matrix, studied for more than 25 years, is now confirmed at the $5.5 \cdot 10^{-4}$ level thanks to major experimental and theoretical efforts, which have allowed a precise determination of the dominant matrix elements V_{ud} and V_{us}. In particular, a careful study of 20 superallowed Fermi transitions, i.e. half-life $T_{1/2}$, branching-ratio *BR* and mass *M* measurements and computation of theoretical corrections [isospin symmetry breaking (ISB) δ_c, radiative corrections (δ_R', δ_{NS} and Δ_R)] to assess their corrected *Ft*-values, has enabled the determination of V_{ud} to a relative precision of $2.2 \cdot 10^{-4}$ (see Fig. 3): $V_{ud} = 0.97417(21)$.

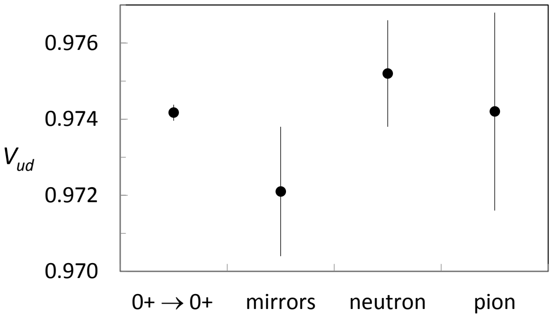

Figure 3. Updated values of V_{ud} from pure Fermi transitions, β transitions of isospin T=1/2 mirror nuclei, neutron decay and pion β decay.

In Europe and worldwide, future plans include:

- Further improvements of experimental data related to superallowed Fermi transitions, to reduce uncertainties on the 14 best studied decays and add new candidates in the previous set, and to improve theoretical corrections, especially the Coulomb correction δ_c, which dominates the uncertainty. Spectroscopic measurements for higher-Z nuclei are advised, as well as measurements in "couples" of superallowed mirror transitions.

- Measurements with the neutron which decays through a mirror transition. In this way, a determination of $|V_{ud}|$ is based solely on two experimental inputs, e.g. the neutron lifetime, and a measurement of one angular-correlation coefficient. The advantage here is the absence of nuclear corrections. However, the two most precise lifetime measurements with ultracold and cold neutrons, respectively, τ = 878.5(8) s and 887.7(23) s, differ by several standard deviations. Thus, if a consistent value for $|V_{ud}|$ is to be derived from neutron decay, the most pressing objective must be to perform more accurate lifetime experiments and to further reduce the uncertainty in correlation coefficients until it is limited by the theoretical uncertainties. Efforts in Europe as well as abroad are under way aiming to push the precision into the few 10^{-4} region. The European lifetime experiments are PENeLOPE, Gravitrap, Hope, τSPECT, and an experiment by Ezhov *et al*., instruments for correlation-coefficient measurements include PERKEO, aSPECT, and NoMoS.

- Measurements in mirror nuclear decays. The V_{ud} value deduced from the study of mirror decays, 0.9719(17), was published in 2009 and is almost a factor of 10 less precise than the result obtained from pure Fermi transitions. As for the neutron decay, the main difficulty here is the need for precise values of the mixing ratios which can only be obtained from correlation measurements in the β transitions. These parameters are the least well-known quantities currently preventing improvement in the precision on V_{ud}. Recent precise measurements of $T_{1/2}$, *BR* and *M*, performed mostly at IGISOL, ISOLDE, GANIL and TRIUMF, could not as yet improve on the precision of the updated V_{ud} value, 0.9721(17), emphasizing the crucial need for correlation measurements. In Europe, two projects are being pursued:
(1) Measurement of the β-asymmetry coefficient A in the ^{35}Ar decay at ISOLDE. In this unique case, a measurement at a 0.5% relative precision would enable to reach a precision on V_{ud} only a factor of ~2 worse than the current best value. There are two experimental approaches for polarizing radioactive nuclei. In the mid-term, it is planned to orient ^{35}Ar ions in a collinear setup, followed by implantation in a crystal. In a longer term, a Magneto-Optical Trap (MOT) will be used to create an ideal polarized ^{35}Ar source.
(2) Measurement of the $\beta-\nu$ correlation coefficient a in several transitions at LIRAT/DESIR (GANIL). The LPCTrap setup will be upgraded to increase the detection efficiency and to better manage systematic effects. The purpose is to measure a at 0.5% in at least four transitions using the new high-intensity beams which should be available at SPIRAL in 2017 (^{21}Na, ^{23}Mg, ^{33}Cl and ^{37}K).
This set of experiments will be completed by further $T_{1/2}$, *BR* and *M* measurements.

Theoretical efforts will also be required to compute radiative and ISB corrections. Various theoretical approaches exist which do not yet provide consistent δ_c values. They need to be studied thoroughly, especially on the basis of specific measurements.

2.2.3 Nucleon and nuclear properties from atomic-physics measurements

Muonic hydrogen and the proton charge radius

The measurement of the proton charge radius by means of laser spectroscopy of the exotic muonic hydrogen atom has yielded a value that is an order of magnitude more precise than the current world average from elastic electron scattering and hydrogen spectroscopy. Surprisingly, the value from muonic hydrogen is 4%, or seven standard deviations, smaller than the value from electronic measurements (see Fig. 4). The proton radius discrepancy has created vivid discussions concerning the accuracies of the charge radius extracted from elastic electron scattering and hydrogen spectroscopy, related to the Rydberg constant. Assuming correctness of the experimental results, no possible explanation within the SM exists. Models of physics beyond the SM have been put forward but none of these has been accepted. Recently, the Lamb shift in muonic deuterium has revealed a deuteron charge radius that is also seven standard deviations smaller than the world average from electronic measurements (see Fig. 4). The two radii from the muonic atoms are consistent with each other. Many new experiments have been triggered by the proton-radius discrepancy: Improved electron-proton scattering experiments at lowest Q^2, muon scattering on hydrogen, improved precision spectroscopy of several transitions in H, D, and He^+, and new measurements in muonic atoms. Several projects aim at a measurement of the ground-state HFS in muonic hydrogen and muonic ^{3}He for a determination of the Zemach radii, a convolution of electric and magnetic form factors. The muonic values can be an order of magnitude more precise than the extraction of those quantities from electron scattering and from spectroscopy of electronic atoms.

Nucleon and nuclear polarizabilities

Uncertainties in nucleon and nuclear polarizabilities limit the accuracy of the charge and Zemach-radius determinations from muonic atoms. The polarizability contributions have to be calculated either from first principles using for example chiral Perturbation Theory, or from measured inelastic Compton-scattering data using dispersion relations (see sec. 4.1.5 of WG1). Alternatively, the polarizability can be determined from the muonic measurements, provided that accurate charge radii are known, for example, from electronic isotope-shift measurements. The measured Lamb shifts in muonic hydrogen and deuterium, combined with the electronic H/D isotope shift, presently yield a three times more precise value for the muonic-deuterium polarizability correction than the one achieved with state-of-the-art EFT calculations. In the chain of helium nuclei, the isotope shifts of (electronic) ^{3,6,8}He have been measured relative to the ^{4}He reference nucleus. A recently completed experiment in muonic helium-3 and -4 will check these isotope-shift measurements, improve the precision in the determination of the absolute charge radii of all helium nuclei by up to a factor of 10, and yield improved values for the nuclear polarizability corrections. Similar improvements can be expected for laser spectroscopy of muonic lithium, beryllium and boron. Of importance will be measurements with tritium atoms, because ^{3}H is the mirror nucleus of ^{3}He. The 1S-2S transition in electronic tritium yields the nuclear charge radius. With this radius, the 2S-2P Lamb-shift measurement in muonic tritium yields the polarizability. A comparison of the electromagnetic properties of the mirror nuclei ^{3}H and ^{3}He would be a unique possibility to improve our understanding of nuclear forces. Another improvement due to muonic-hydrogen spectroscopy can be expected in one of the oldest QED tests, namely the HFS in electronic hydrogen. This famous 21cm line has been measured to six parts in 10^{13} in the 1970s already, but the theoretical prediction is limited to the 10^{-6} level because the proton spin-dependent polarizability contribution is poorly understood. A tenfold improvement may seem possible with the measurement of the muonic-hydrogen HFS and investigation of the corresponding proton-polarizability correction.

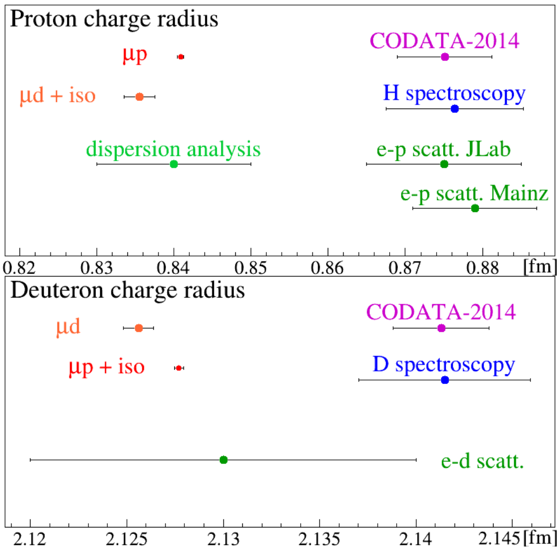

Figure 4. The rms charge radii of proton (top) and deuteron (bottom) as determined by different methods (elastic electron scattering, electronic and muonic H and D spectroscopy, combination of the optical isotope shift measurement with muonic atom results) indicating the discrepancy between the muonic-atom and the electronic results. Also shown are analyses of electron scattering data using dispersion relations, and the CODATA world average.

Combining muonic-atom spectroscopy with elastic electron scattering

The charge radius of a nucleus appears as the slope of the electric form factor (FF) measured in elastic electron scattering (see sec. 4.1.5 of WG1). Once the proton-radius discrepancy is resolved, one can gain new insights into the structure of the nucleon when one fixes the slope of the electric form factor, i.e. the Q^2 term of $G_E(Q^2)$, to the precise value obtained from the charge radii measured in muonic-atom spectroscopy. This will yield more precise values for the Q^4 term of G_E, the Q^6 term, etc.

Similarly, the Zemach radii can be calculated from the measured electric and magnetic form factors, G_E and G_M, respectively. The Zemach radii can also be determined from measurements of the HFS in muonic atoms.

Thus, such a muonic HFS should improve the magnetic FF similar to the impact of the charge radius on the electric FF. In addition, polarizabilities determined from a combination of muonic- and electronic-atom spectroscopy can serve as further stringent constraints on nuclear two-photon physics derived from Compton-scattering data.

Heavy muonic atoms

Charge radii of medium-to-high-Z nuclei have been measured since long by means of muonic-atom x-ray spectroscopy. The availability of negative muons with very low kinetic energies will allow extending such measurements to radioactive nuclei for which only minute quantities of a few micrograms can be used. Such projects are being pursued at J-PARC and at PSI.

Kaonic atoms

Precision measurements of kaonic atoms, where a negatively charged kaon replaces an electron in a highly excited orbit, followed by de-excitiation and detection of the emitted radiation, will be performed at the DAFNE Collider at LNF-INFN and at J-PARC. These measurements allow to determine the antikaon-nucleon isospin dependent scattering lengths which are relevant for the understanding of low-energy QCD in the non-perturbative regime (see sec. 4.1.6 of WG1), crucial to comprehend the chiral-symmetry-breaking mechanism giving mass to the baryonic matter in the Universe. These studies also help to tune the neutron stars' equation of state connected to the characteristics of gravitational waves emitted by binary neutron-star systems, which are expected to soon be measured by interferometric gravitational antennae. Kaonic deuterium will be measured by SIDDHARTA-2 for the first time in the coming years. By using new types of detectors, such as Transition Edge Sensors, other types of kaonic atoms, including kaonic helium-3 and 4 (transitions to the 2p and 1s level) and kaonic nitrogen will also be measured to high precision. These measurements will allow extracting the mass of the negatively charged kaon with a precision of a few keV, solving a long-standing puzzle involving this fundamental quantity. Laser spectroscopy of exotic atoms beyond positronium and muonium was pioneered with antiprotonic helium at CERN and with muons at PSI. A project aiming at laser spectroscopy of pionic helium is under way at PSI. Feasibility of laser spectroscopy of kaonic atoms will be explored for the first time, which may allow further improvements in the precision of these types of measurements.

Precision nuclear spectroscopy of thorium-229

The nuclear level structure of ^{229}Th shows a unique low-energy isomer state, only 7.8(5) eV above the ground state, corresponding to an excitation wavelength of about 160 nm in the ultraviolet range. ^{229}Th is so far the only known isotope with the potential to drive a nuclear transition with (laser) light, bridging the gap between nuclear and atomic physics. In particular, techniques from high-precision spectroscopy and quantum optics can be transferred to the nucleus. The expected long lifetime and a corresponding narrow linewidth, plus the intrinsic robustness of nuclear quantum states against external perturbations, make this system an excellent candidate for a new time standard with the potential to outperform current optical atomic clocks and to reach 10^{-19} precision. The exact isomer energy and hence the transition frequency is determined by the nuclear energy scales involving the weak, the strong, and the electromagnetic forces. Reaching atomic-spectroscopy precision in this nuclear transition increases the sensitivity to temporal variations of fundamental constants by many orders of magnitudes. Optically driving the thorium transition would become the primer for a new emerging field of nuclear quantum optics and metrology.

3. Searches beyond the SM

3.1 Fundamental-symmetry tests

Testing fundamental symmetries and related conservation laws is a prime route toward establishing the limits of the SM. Experiments at low energies can be particularly sensitive due to the availability of well defined systems, of high-precision spectroscopy methods and of high particle intensities. Test of symmetry violations comprise those of the fundamental discrete symmetries of parity (*P*), time reversal (*T*), charge conjugation (*C*) and their combinations *CP* and *CPT*. Searches for *CP* and *T* violation beyond that found in meson physics are greatly motivated by the observed BAU and also by the natural appearance of *CP* violating phases in extensions of the SM. The search for *T* violation with EDM and weak decays and measurements of *P* violation in atomic and molecular systems are especially powerful. A similar motivation fuels searches for *L* and *B* violations which might help understanding BAU. Such violations may have a close connection to the unknowns of neutrino physics, to Grand Unification and in general to the beyond SM physics as parametrized for instance in the SMEFT. We emphasize here the importance of the *L* violating $0\nu\beta\beta$ decay searches, the most sensitive cLFV decays of muons, and, besides the search for the ΔB=1 violating proton decay with large-mass neutrino detectors, the discovery potential of a new search for the ΔB=2 violating oscillation of neutrons to antineutrons.

Searches for *CP* and *T* violation

Permanent electric dipole moments (EDMs) violate both *P and T* symmetry. They offer a promising route for exploring additional sources of *CP* violation and to explain the matter-antimatter asymmetry. The discovery potential of searches for EDMs has led to a number of experiments on different systems. There are searches for the neutron EDM with the promise of 1-2 orders of magnitude improved sensitivities compared to the present limit of $d_n < 3.0 \cdot 10^{-26}$ e·cm (90% C.L.). In Europe these efforts rely on improved neutron sources at PSI, ILL and at the future ESS. Experiments with atoms, molecules, and ions exploit large enhancement factors in composite systems. Such enhancements can be up to of order 10^6 for the electron EDM in heteronuclear molecules. This enabled a strong recent limit on the electron EDM $d_e < 1.1 \cdot 10^{-28}$ e·cm (95% C.L.) using ThO molecules. Such an approach can be expected to deliver more stringent limits due to improved experimental techniques for a variety of molecular systems (YbF, ThO, BaF, HfF^+). The combination of large EDM enhancement factors and extended coherence and observation times in beams of slow molecules will further significantly improve the sensitivity to d_e.

A theoretical framework is required to disentangle hypothetical sources for CP-violation. Composite systems are sensitive to various *CP* violating sources and the ThO EDM experiment presently also sets the most stringent bound on *CP* violating electron nucleon couplings. The tightest bound on a nuclear EDM arises from an atomic ^{199}Hg experiment, $d_{Hg} < 7.4 \cdot 10^{-30}$ e·cm (95% C.L.), which constrains various *CP* violating effects involving gluons, quarks, nucleons and electrons.

Improvement in shielding and compensation of magnetic fields and gradients is essential for increasing the sensitivity of current experiments. Similar to the neutron EDM search where a co-located ^{199}Hg magnetometer allowed for major progress, gas mixtures of hyperpolarized ^{3}He and ^{129}Xe are exploited to search for the EDM of ^{129}Xe with ^{3}He as co-magnetometer. Here coherence times of several thousand seconds and large numbers of particles offer a potential improvement of up to four orders of magnitude over a previous bound in ^{129}Xe, which is approximately equivalent to an improvement of two orders of magnitude over the present ^{199}Hg results.

Another approach towards measuring EDMs employs light charged particles or nuclei in electric and/or magnetic storage rings. In such an experiment, an EDM could manifest itself as an out of orbit-plane precession of the particle spin. Here the rather high motional electric field which a stored particle experiences when it moves in the storage ring is exploited. The experiments, in Europe for the proton and the deuteron within the JEDI collaboration, are in development stages concerning equipment and principal experimental techniques. As a proof-of-principle, the last g_μ-2 storage-ring experiment delivered a direct limit on the muon EDM $d_\mu < 1.8 \mathrm{x} 10^{-19}$ e·cm (95% C.L.).

Complementary to the search for permanent EDMs is the measurement of triple correlations in nuclear and neutron β decays. Among these correlation parameters, *D* appears particularly interesting:

$$D \propto Im\{|M_F||M_{GT}|C_V C_A^*\}$$

where M_F (M_{GT}) is the Fermi (Gamow-Teller) nuclear matrix element, C_V and C_A are the vector and axial-vector coupling constants, respectively. The *CP* (or equivalently *T*) violation contribution in *D* would thus come from a phase between vector and axial-vector couplings, and its measurement makes sense only in mirror transitions of oriented nuclei. In this case, the required detection setup is another configuration of the setup used for $a_{\beta\nu}$ measurements. Collinear laser spectroscopy systems are suited for the polarization of nuclei like ^{23}Mg and ^{39}Ca which decay through mirror transitions. The degree of polarization expected with ions confined in traps is close to 99%. The measurement of *D* in mirror decays employing traps is therefore an interesting opportunity in the future to lower the uncertainties below 10^{-4}.

Significant efforts on theoretical approaches are also essential to guide development of specific experiments and explore possible interpretations of results from different sources (EDM, *D*) with minimal model dependences. Here, the SMEFT offers great insights.

Another *T* violating observable is studied by TRIC (Time Reversal Invariance at COSY) at FZJ which aims at improving the sensitivity to time reversal at least by one order of magnitude. The total cross section for the interaction of protons and deuterons with both species polarized will be extracted from the measurement of the lifetime of the coasting COSY beam for two spin-orientation scenarios equivalent to time reversal.

P violation in atoms, ions and molecules

The electroweak unification in the SM predicts observable contributions from the weak interactions in atomic and molecular spectra. Here the strength of the weak interactions, i.e. the nuclear spin independent weak charge, and the weak induced nuclear moments, such as the anapole moment, are investigated. The best quantitative measurement of weak effects in atoms comes from Cs and has generated detailed theoretical studies of atomic parity violation. Progress achieved by improved atomic and molecular theory together with experimental techniques lead to a selection of most sensitive systems.

Heavy diatomic molecular systems and heavy elements, e.g. ytterbium and dysprosium, are considered promising choices for measurements of nuclear anapole moments. Advances in slowing, cooling and trapping of molecules together with an enhanced intrinsic sensitivity due to the abundance of near degenerate states enable quantitative measurements of the weak interaction in nuclear matter. Other approaches to measure parity-violation effects include precision studies of selected transitions in chiral molecules and detecting subtle effects in nuclear magnetic-resonance experiments. The spin independent contribution is strongly enhanced in heavy atomic systems (stronger than Z^3). The best quantitative treatment of these many-electron systems is achieved in single-valence-electron systems such as alkali atoms and alkaline-earth ions. Several experiments are under way on radioactive francium isotopes which can be produced in sufficient quantities and confined in atom traps. The alkaline-earth ions Ba^+ and Ra^+ are currently employed in experiments aiming at a fivefold improvement in the determination of the weak-interaction parameters of the SM. Such precise determinations may also be sensitive to extensions of the SM which introduce additional heavy bosons, e.g. Z’ or light dark matter Z_{dark}.

Searches for CPT and Lorentz violation

A direct sensitive test of *CPT* invariance is to measure properties like masses and *g*-factors for both particles and anti-particles. The masses of the neutral kaon and antikaon presently provide the most precise comparison, with a relative difference at the level of 10^{-18}. Figure 5 shows the accuracy reached in various *CPT*-invariance tests. The charge-to-mass ratio of the proton and antiproton was compared at LEAR and at AD (both at CERN) via measuring cyclotron frequencies in a Penning trap. The difference was found to be less than 10^{-10}. A similarly stringent *CPT* test is possible by comparing the magnetic moments of the proton and antiproton stored in a Penning trap. First precision measurements at the level of 10^{-6} have been carried out recently by ATRAP and BASE. Further orders-of-magnitude improvements are expected in the coming years. At present, the only facility to perform such experiments is the AD, constructed in 1999 in order to test *CPT* invariance with antiprotons and antihydrogen. The AD experiments ALPHA and ATRAP have produced and confined antihydrogen atoms. ALPHA carried out first microwave spectroscopy of antihydrogen trapped in a Ioffe-Pritchard trap. An upper limit on the charge of antihydrogen was established, from which, in combination with upper limits on differences between proton and antiproton, a CPT test at the 10^{-9} level for the relative differences of the electron and positron charges and masses is derived. The ASACUSA collaboration has produced and studied antiprotonic helium. In combination with the Penning-trap measurements, the mass, charge, and (at a lower precision) magnetic moment of the antiprotons was extracted providing a sensitive test of *CPT*. More recent approaches to produce an atomic beam of antihydrogen, a technique also pursued by AEGIS, open up further spectroscopic opportunities. To accommodate the expanding community including GBAR, a further deceleration stage, the ELENA storage ring, has been built and is undergoing commissioning. Possibilities for the longer-term future are provided by the FAIR facility at GSI.

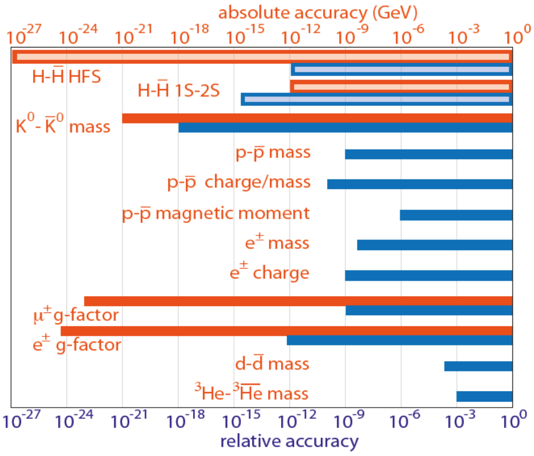

Figure 5: Comparison of several CPT tests in terms of relative accuracy (blue) and absolute accuracy (red) based on the SME model. Values for hydrogen–antihydrogen comparison assume that antihydrogen will be measured to the accuracy that has been achieved for hydrogen.

While *CPT*-violation searches involve antimatter probes, *CPT* violation is often related to Lorentz invariance (LI) violation. LI is a corner stone of modern Quantum Field Theories and as such should be tested experimentally. A popular framework in which LI tests are often analyzed is called Standard Model Extension (SME) not to be confused with the SMEFT. The SME includes the SM, but also gravity, and allows intercomparison of different LI tests as the observables can be expressed via the theory parameters. In general, many time stamped precision experiments can be analyzed to constrain the SME parameters. Some experiments test isotropy of space, for example, by comparing the velocity of light in different directions or comparing precession of spin clocks (such as neutrons or ^{3}He) around different axes. While particularly stringent tests were performed in the electromagnetic-interaction sector, weak interactions and higher-generation particle observables have moved into focus more recently.

Spin-statistics tests

The concept of *identical particles* is unique to quantum physics. In contrast to, for example, identical twins or the so-called “standard-candle” supernovae, all electrons, helium atoms, ^{85}Rb nuclei, etc., are, as far as we can tell, *truly* identical to each other. This means that if we have a wavefunction representing a system containing identical particles, particle densities should not change upon interchange of two of these. As a consequence, the wave function should either remain invariant or change sign under permutation of identical particles. This is the essence of the permutation-symmetry postulate (PSP). The spin-statistics theorem (SST) relates, one might argue, a-priori unexpectedly, which of the two options is realized, to the intrinsic spin of the particles. The resulting division of particles into fermions and bosons is one of the true cornerstones of modern physics. SST is proved in the framework of relativistic field theory using the assumptions of causality and Lorentz invariance in 3 + 1 spacetime dimensions, along with a number of subtler implicit assumptions. While it is difficult to build a consistent relativistic theory incorporating SST and PSP violations, it is important to put these properties to rigorous tests given their fundamental importance in our understanding of nature. One may think of such a test as probing all the assumptions in the SST proof, as well as a possible experimental window into theories that go beyond the conventional field theory, for instance, string theory. Since all our observations so far are consistent with PSP and SST, the experiments should search for *small* violations of PSP and SST.

Molecular spectroscopy has played an important historical role in establishing the experimental basis for PSP and SST. The general idea is that in a molecule containing two identical nuclei and assuming, for example, a symmetric electron-spin state, rotational states corresponding to the overall molecular wavefunction being symmetric (in the case of half-integer-spin nuclei) or antisymmetric (in the case of integer-spin nuclei) are forbidden by quantum statistics, and so the lines involving these molecular states are absent from the molecular spectrum. A powerful experimental methodology for testing for statistics violations is to look for such forbidden lines. Recent experiments using $^{12}C^{16}O_2$ molecules containing two bosonic oxygen nuclei limited the relative probability for the molecule to be in a wrong-symmetry state at a $<3.8 \cdot 10^{-12}$ level. An interesting extension is to molecules containing more than two identical nuclei that would allow to probe for more complex permutation symmetries than are allowed for just two identical particles. Another recent experiment using two-photon optical transitions in barium limited the probability of two photons being in a wrong-symmetry (i.e., fermionic) state at less than a part in $4 \cdot 10^{11}$.

Other experiments check for forbidden atomic or nuclear transitions. A particular consequence of the SST is the Pauli Exclusion Principle (PEP), permitting only two electrons in a given state, for instance, the 1s ground state of copper. A limit on the probability for an additional electron in copper to form a mixed-symmetry state constraining PEP violation at the level of $<4.7 \cdot 10^{-29}$ was set by the VIP experiment at LNGS. The successor VIP2 aims to improve the sensitivity by two orders of magnitude.

Similar to SST tests, also rigorous tests of quantum mechanics investigate foundations of our theoretical understanding of Nature. Experiments testing quantum mechanics and its possible limits use various systems, such as elementary particles, photons, neutrons, nuclei, atoms, and molecules. Also these tests will continue in the coming years with ever increasing sensitivity, while having a broader positive impact on quantum technologies.

Search for cLFV

The violation of lepton number is directly searched for in $0\nu\beta\beta$ experiments (see above). Lepton-flavour violation is, in fact, established in neutrino oscillation. With a large suppression, this also induces cLFV. However, a strong motivation for much enhanced cLFV comes from beyond-the SM models which do not explicitly suppress it by additional assumptions. cLFV searches in muon decays have a long history and so far only set upper limits, see Fig. 6. The most stringent limit on any forbidden or rare decay comes from the MEG experiment at PSI: $BR(\mu \rightarrow e\gamma) < 4.2 \cdot 10^{-13}$ (90% C.L.). International collaborations aim at considerable improvements of sensitivity of their search experiments, MEG II at PSI aims at $5 \cdot 10^{-14}$, Mu2e at FNAL and COMET at J-PARC search for the conversion of negative muons $\mu \rightarrow e$ bound to nuclei aiming at 10^{-16} and the Mu3e at PSI will search for neutrinoless $\mu \rightarrow eee$ decays in two steps pushing to 10^{-15} and 10^{-16}, respectively. All these experiments need high-intensity muon beams with different characteristics, pulsed ones at FNAL and J-PARC and continuous beams at PSI. Recently, options to also probe some more exotic cLFV channels at higher sensitivities are receiving renewed interest. Efforts to search for muonium to antimuonium oscillations can be seen in a similar context as neutron to antineutron oscillations.

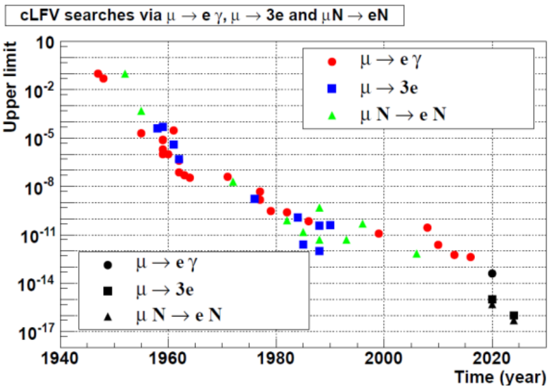

Figure 6: Upper limits (90% C.L.) on decay branching ratios obtained in the searches for muonic cLFV over the years (color symbols). The latest $\mu \rightarrow e\gamma$ limit ($4.2 \cdot 10^{-13}$) represents the most sensitive of any rare decay search so far. Various projects aim at improving one of these three 'golden' channels (projected sensitivity limits: black symbols).

3.2 Dark Matter, Dark Energy and exotic forces

Cosmology has reached an unprecedented level of precision with the standard cosmological (so-called ΛCDM) model fitting very well all the vast amount of presently available observational data. This standard model of cosmology describes our present Universe and its evolution starting from the Big Bang. However, for the good agreement between data and the model, 95% of the energy content of today's universe needs to be assigned to yet unknown kinds of matter and energy, whereas less than 5% is attributed to normal matter consisting of atomic nuclei and electrons.

Gravitational effects on all scales from galactic (rotation curves) to cosmological ones suggest exotic "Dark Matter" outbalancing normal matter by a factor of five. An alternative approach, modifying the laws of gravity (MOND: modified Newtonian dynamics) runs into difficulties explaining the observations on all those scales. The accelerated expansion of the Universe is attributed to “Dark Energy” contributing about 70% of its energy content.

What is the origin of this “Dark Sector”? It is likely that Dark Matter consists of a new kind of exotic massive particle interacting only “weakly” in addition to gravitationally. Here “weakly” does not necessarily mean the interaction via Z and W bosons. Particle physics beyond the SM provides possible Dark-Matter candidates on a stunningly wide mass scale (see Fig. 7), among which the following three are most favored today: weakly interacting massive particles (WIMPs), sterile neutrinos with keV masses (Warm Dark Matter), and axions and axion-like particles (ALPs). The formation of the large-scale structure of today’s Universe requires that the dark-matter particles were non-relativistic at structure formation (“Cold” or “Warm” Dark Matter).

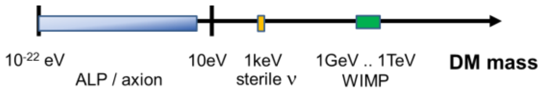

Figure 7: The masses of viable Dark Matter candidate particles span an extremely wide range. Only some of the present candidate particles are displayed.

Regarding today’s accelerated expansion of the Universe, while it could be explained just by a non-zero value of the cosmological constant Λ of Einstein’s general relativity, from the particle-physics perspective, it would be natural to associate the accelerated expansion with a new light scalar field.

Many models which introduce new Dark-Sector particles also allow for their, usually feeble, interactions with ordinary matter. Therefore, low-energy precision experiments can test such models searching for deviations in the interaction of particles from their expected SM or standard-gravity behavior. One example is the search for ALPs via exotic spin-dependent forces. As another example, some theories of Dark Matter and Dark Energy predict deviations from the Newton’s inverse square law of gravitation at short distances, which has been tested down to 20 μm.

A gravitational quantum theory in the elementary-particle domain has not been established yet. Evaporation of black holes suggests quantum effects of gravitation, but a complete theory does not as yet exist. Therefore, we are still at the stage of collecting empirical data on possible options of gravitational interactions. While gravitational matter-matter interaction has been shown to be universal for macroscopic test masses at a level of a part in 10^{12} and to high precision also for free-falling atoms and neutrons, a direct test of the universality of free fall is still missing for antimatter. Deviations from the known interactions would show up as exotic forces and would most likely be connected to yet unknown particles.

3.2.1 Direct Search for Dark Matter Particles

Complementary to indirect searches for Dark Matter by looking for products of Dark Matter self-annihilation with neutrino, gamma and charged-particle telescopes, to production of Dark-Matter particles at LHC, and to the search for solar axions with helioscopes, are direct searches for Dark-Matter particles in the Milky Way. A detection of such particles would be a reliable proof of the existence of exotic Dark Matter in our galaxy.

Theories beyond the SM provide plausible Cold Dark Matter candidates. Especially in supersymmetric extensions of the SM (SUSY), WIMPs with masses of several tens of GeV to TeV would have been produced naturally in the right amount in the early Universe. Ultra-sensitive experiments in underground laboratories, for example, dual-phase xenon or argon time-projection chambers like LUX, XENON1T, and DarkSide, are looking for the scattering of WIMPs off nuclei. They have reached sensitivities to WIMP-nucleon elastic scattering cross sections of 10^{-45} cm^2 and below. An improvement in sensitivity by another 2-3 orders of magnitude is expected with these techniques by increasing detector masses and lowering backgrounds within the next decade. Examples of such experiments are XENONnT, DarkSide-20k, ArDM and DARWIN in Europe. Cryogenic bolometers, for example CRESST and EDELWEISS, complement these searches for WIMPs with masses down to the GeV range.

Although the structure formation in the Universe and direct neutrino mass limits exclude the possibility that normal neutrinos make up a large fraction of Dark Matter, sterile neutrinos with keV masses are an interesting alternative for Warm Dark Matter. They can be searched for with direct neutrino-mass experiments or by looking for their decay into standard neutrinos and photons with x-ray telescopes.

Finally, axions and axion-like particles are interesting candidates for Dark Matter. The axion, a hypothetical elementary particle arises in the Peccei-Quinn theory and resolves the problem of non-observation of *CP*-violation in strong interactions that would manifest itself, for instance, as neutron EDM. Strong *CP* violation naturally appears in Quantum Chromodynamics and its absence is puzzling without invoking the axion. Experimental, astrophysical, and cosmological limits have been refined and indicate that axions – if they exist – have to be very light with masses in the peV to meV range. Still, they are counted as Cold Dark Matter. They are searched for in laboratory experiments using Primakoff conversion into microwave photons in a strong magnetic field, for example, in the ADMX experiment. Since the Sun rotates with a velocity of 230 km/s around the center of the Milky Way, our laboratories move with respect to the Dark Matter halo with that velocity additionally modulated by the rotation of the earth. This can be used to look with atomic magnetometers, ultracold neutrons and clocks for periodic modulations due to ultralight bosonic particles that could be components of Dark Matter or Dark Energy.

3.2.2. Test of Dark Energy models with precision experiments

Cosmology with Dark Energy caused by light scalar bosons can be made acceptable by invoking a late stage of inflation with the Hubble constant H_0 less or approximately equal to the mass m_ϕ of the scalar boson. A chameleon field as a realization of such a scalar field called quintessence may couple to ordinary matter and mediate a long-range force, which would show up in the fifth-force searches or equivalence-principle tests.

Today chameleon fields are strongly constrained by precision experiments. A significant step forward was made by analyzing gravitational quantum states of neutrons bouncing above a flat surface and by neutron-interferometer experiments. In another approach, an atom interferometer allowed to look for changes in the accelerations of caesium atoms near a spherical mass as a source of chameleon fields. These experiments exclude the chameleon theories that could account for Dark Energy with a coupling constant $\beta > 4.3 \cdot 10^4$. Pushing the sensitivity limit to $\beta < 1$ would completely exclude these classes of chameleon theories.

3.2.3 Exotic forces

Beyond-the-SM particles that may constitute the Dark Sector may modify the known interactions and manifest themselves as exotic forces, e.g. the “fifth force” between two masses. In addition, the “new” particles may couple to charges and spins, producing a variety of possible exotic interaction potentials. For a set of generic assumptions for spin-0 or spin-1 bosons, there are 16 independent potentials in the nonrelativistic limit, the simplest of which is the Yukawa-type coupling. The axion can produce such a coupling with the strength $g_s g_p/\hbar c$, where $g_{s,p}$ characterize the scalar and the pseudoscalar interaction, respectively. The most restrictive limit on $g_s g_p/\hbar c$ was derived by combining the laboratory limit on g_s with stellar energy-loss limits on g_p, which is more stringent than laboratory searches alone.

Various kinds of exotic interactions are currently being probed in a plethora of atomic and molecular systems, including comparison of the experimental and theoretical spectra for relatively simple atoms (helium, positronium), precision measurements of the interaction between trapped ions, comparisons of theory and experimental data for spin-dependent intramolecular interactions (for example, in the HD^+ ion where sub-ppb comparison of experiment and theory was recently achieved). While these experiments probe short-range interactions, similar approaches for long-range forces exist. Test laboratory masses and spin-polarized samples are used to “source” exotic fields that can be probed with atomic magnetometers, as well as with devices sensitive to variation of fundamental “constants.” The advantage of the laboratory sources is that they can easily be manipulated to modulate the signal.

Possible Yukawa-type generalisations of Newton’s gravitational potential can be written as

$$V(r) = -G/r \cdot m_1 \cdot m_2 \cdot (1+\alpha\, e^{-r/\lambda}),$$

where α is a dimensionless strength factor in comparison with Newtonian gravity and λ is the characteristic Yukawa distance over which the corresponding force acts. In the range $\lambda >$ 20 µm, the Seattle torsion-pendulum experiments find no deviation from Newtonian physics. An Atomic Force Microscope was used to perform measurements of the Casimir force and deduced constraints on α and λ at micron distances. Free-falling atoms can be used to probe sub-micron forces by interferometry of Bose-Einstein condensates. Another approach is to explore a single particle, for example a neutron falling in the Earth's gravity in conjunction with a massive object, a mirror, from which the neutron bounces off. In addition to probing for the extra bosons as discussed above, searching for deviations from Newton's gravitational law also probes for other kinds of new physics, such as various forms of extra dimensions. Such experiments are performed by the *q*BOUNCE and GRANIT collaborations. The use of neutrons as test particles bypasses the electromagnetic background induced by van der Waals and Casimir forces and other polarizability effects.

A class of experiments tests the universality of gravity and the equivalence of the gravitational and inertial mass. Indeed, the universality of the acceleration of free fall has been verified at the 10^{-13} level for laboratory bodies, notably Be-Ti, and Be-Al test masses. A phase shift induced by gravity has been measured in matter-wave interferometers operating with laser-cooled ensembles of ^{87}Rb and ^{39}K atoms. The experiments show that there is no difference in free fall between the two ensembles on the 10^{-7} level. Studies with neutrons have so far reached an accuracy of $3{\cdot}10^{-4}$ in confirming that the ratio m_i/m_g is equal to unity.

Equivalence tests with antimatter have included comparisons of gravitational red shift for trapped charged particles and antiparticles, but are currently focusing on antihydrogen, which should be compared to ordinary hydrogen using the most sensitive atom-interferometry and spectroscopic methods. Initial attempts at much lower sensitivity have already begun: the AEGIS, ALPHA and GBAR experiments at the AD facility at CERN aim to measure the gravitational mass of antihydrogen atoms with a precision in the 0.1-10% range. In spite of the initially modest precision, the first direct measurement of a gravitational effect on antimatter will be scientifically relevant and will pave the way for higher-precision studies. These endeavors will benefit in particular from the increased antihydrogen production rates at ELENA. In the longer term, higher sensitivity might be possible via spectroscopic studies of gravitational quantum states if sufficiently cold antihydrogen atoms can be prepared. In addition to antihydrogen, the study of the gravitational interaction of antimatter appears feasible and is pursued in Europe with the purely leptonic positronium and muonium. The latter is dominated in mass by the second generation antimuon. Initially, measurements of the annual red-shift modulation of the 1S-2S transition frequencies could determine the sign of their gravitational interaction. Atom interferometry methods could eventually lead to a precision of 1-10%.

3.3 Temporal and spatial variation of fundamental constants

It is now generally accepted that the Universe has undergone a period of rapid inflation in its early stages, during which the laws of physics in the way we normally think about them have also changed. It is thus logical to ask whether the laws of physics encoded in the values of fundamental "constants" may be evolving even after the inflation is over. In fact, the question of stability of the constants goes back to Paul Dirac. As all other basic laws of physics, the usually assumed stability of fundamental constants requires rigorous experimental verification. One way to look for possible variations of constants is observing absorption spectra of quasars, bright broadband light sources that are at "look-back" times from us comparable to the lifetime of the Universe (~10^{10} y). As the light from quasars travels towards us, it undergoes absorption by atoms and molecules in the interstellar media. Once we detect the corresponding absorption lines via astronomical observations, we can correct the spectra for the red shift, and compare them with the spectra recorded in the laboratory. A change in fundamental constants, for instance, the fine-structure constant α is revealed in the difference of the spectral profiles. In fact, by the late 1990s, there appeared evidence that α may have been approximately one part in 10^{10} smaller in the early Universe than it is today. Interestingly, assuming a constant rate of variation, this would mean a fractional variation of α at a ~10^{-15}/y level, not too far from the stability level of the state-of-the-art atomic clocks at that time. This led to a rapid development of laboratory experiments searching for present-day variations of constants.

The current situation is that there is no uncontested spatial or spatio-temporal variation of any of the dimensionless fundamental constants, although the searches are rapidly improving, especially on the laboratory side, where the level at which the variation is being probed is already better than ~ 10^{-17}/y. The above mentioned possibility to exploit the ^{229}Th nuclear clock transition might allow for further considerable improvements. Moreover, it has been realized that laboratory experiments can be sensitive not only to a monotonic drift of the constants, but also to their oscillating and transient behavior. Such time-dependent effects can be related, for example, to ultralight scalar fields that are part of Dark Matter, and the experiments of this type are opening a completely new window into the study of Dark Matter.

4. Future directions

The research of "Symmetries and Fundamental Interactions" covers a huge range of physics questions which are all aimed at discovering and testing the most basic laws of Nature, Matter and the Universe. Although there has been tremendous progress made since the last Long Range Plan in many research areas, among others by setting new stringent limits e.g. on the unitarity of the CKM quark mixing matrix, the neutrino mixing angles and the validity of quantum electrodynamics in strong fields, there is still the quest for ever more precise tests. To this end the researchers are combining and applying the most sensitive methods of a variety of fields. However, most often the success depends on the available expertise in experiment and theory as well as on the available beamtime, beam intensities and cleanliness of the beam of the particles of interest at the European facilities. Thus, NuPECC's focus should be concentrated on state-of-the-art possibilities to achieve the goals in the field and to pave the way for potentially important discoveries.

In the following, some future directions in the field of "Symmetries and Fundamental Interactions" shall be given:

Electroweak Interaction

The advances in technology and techniques, in particular regarding trapping, lasers, high-precision frequency measurements, detector technology, particle beams and particle manipulation have allowed for considerable progress in the determination of fundamental parameters and quantities like masses, electromagnetic moments, lifetimes and weak decay correlations. They have also opened several windows for further large steps forward, both in technology development and in physics reach. We expect on the one hand improved tests of QED, pushing into a region where they become more and more sensitive to weak, hadronic and nuclear corrections. These will allow testing our understanding of such corrections but also, by clever experiment selection, to cancel them to a large degree and extract fundamental constants. On the other hand major progress in nuclear and neutron decay experiments will push several weak observables into the sub per mill accuracy region. This will provide unprecedented constraints on possible exotic extensions of the standard weak interaction theory. Precision experiments turn more and more into most powerful search experiments for deviations of the standard theory providing a huge discovery potential.

Neutrinos

Although the still unknown neutrino mass scale is being scrutinized more and more by cosmology the efforts to measure it in laboratory experiments needs to be continued both by direct experiments investigating the kinematics of beta decays or indirectly by the search for neutrinoless double beta decay. Novel concepts in direct neutrino mass experiments may allow to improve the sensitivity below 100 meV in future. Neutrinoless double beta decay searches with ton-scale masses may reach half-life sensitivities of 10^{27} yr and beyond not only probing the neutrino mass to the sub-100meV level but also lepton number violation and the various beyond the Standard Model scenarios of neutrino mass generation. These experiments need to be accompanied by theory efforts to understand better the nuclear matrix elements of neutrinoless double beta decay.

Neutrino oscillation experiments with reactor, accelerator and atmospheric neutrinos will allow to determine the neutrino mass hierarchy within the next decade. The determination of a finite CP-violating phase in the neutrino sector aimed for by accelerator neutrino experiments might complete our understanding of the neutrino mixing matrix. Searches for a forth or fifth generation of (sterile) neutrinos may provide us new surprises.

Fundamental Symmetries

Tests of C, P and T, both individually and in combination, immediately benefit from ongoing advances in experimental techniques, such as improved trapping and cooling of atoms, ions and molecules, or enhanced production rates of specific isotopes or accelerator-produced particles such as neutrons, muons and antiprotons. In parallel, focus is increasingly also shifting to tests of fundamental assumptions (such as the Pauli exclusion principle, lepton number and charged lepton flavor conservation, Lorentz Invariance and others) where a number of experiments are poised to improve sensitivities by several orders of magnitude in the coming few years. Similarly important, experiments will further explore and improve sensitivities to various Dark Matter and Dark signals and provide competitive constraints. Tests of the WEP with antimatter (using antihydrogen, positronium and muonium) underline the importance of a range of complementary approaches to ensure that first rough measurements are obtained already in the near future, while higher precision measurements possibly building on these could easily take a decade.

5. Recommendations

Mandatory for the achievement of the above listed challenging goals are an appropriate funding and environment including adequate academic positions for young researchers and state-of-the-art facilities. Three central priorities have been identified:

Priority 1.

Support of small-sized laboratories and university groups

Many of the precision experiments to study fundamental interactions require dedicated table-top setups in small-size laboratories at universities where they can either be pursued or where innovative techniques are tested before they get installed at larger online facilities and large-scale infrastructure. Common to almost all experiments in the field of precision tests of fundamental symmetries and their interactions are cooling and storing. To that end, charged as well as neutral particle traps need to be improved to extend their applicability, to increase their sensitivity and accuracy as well as to address new observables.

Priority 2.

Theory support

High-precision measurements of fundamental physical constants, low-energy tests of the Standard Model, and searches for new physics in high-precision spectroscopic measurements require accurate theoretical descriptions of atomic and molecular states. In addition to the appropriate treatment of QED and weak-interaction effects, one has to account for the influence of nuclear structure which is often a major source of theoretical uncertainties. Moreover, for the comparison of sensitivity of new physics searches at different energy scales it is important to interconnect them by using the same theoretical framework. Most importantly, theoretical guidance and new ideas are indispensable to open up new research fields. For these reasons, continued or even stronger support for theoretical research groups, as well as for theorists “embedded” in experimental groups is required.

Priority 3.

Facilities

For the exotic systems to be investigated, whether antimatter, cold and ultracold neutrons, short-lived radionuclides, highly-charged ions, muons or muonic as well as other types of exotic atoms, dedicated laboratories with intense sources are indispensable. Progress in precision measurements and searches for physics beyond the Standard Model through studies of symmetries and fundamental interactions relies, among other things, on the development of intense sources. Upgrades and support of existing small facilities as well as large scale infrastructure in Europe, including underground laboratories and accelerators, to provide sufficient access and beam time is thus mandatory to push the limits of the present best experiments and to allow for new dedicated setups.