Abstract
In the field of fundamental interactions and symmetries numerous experiments are underway or planned in order to verify the standard model in particle physics, to search for possible extensions to it or to exploit the standard model for extracting most precise values for fundamental constants. We cover selected recent developments, in particular such which exploit stored and confined particles. Emphasis is on experiments with transformative character, i.e. such which may be able to guide and steer theoretical model building into new but defined directions. Among those are projects with antiprotons, muons and certain selected atoms and atomic nuclei.

Keywords: fundamental interactions, precision measurements, standard model

1. Introduction
With the successful start of data taking at the CERN LHC facility, the discovery of the Higgs boson [1, 2], the recent LHC energy upgrade and prospected running of the facility for at least one decade to come, we can anticipate scrutinizing of all high energy particle physics up to LHC energies with utmost care. As energies at LHC and possible future accelerators are limited, potential New Physics at higher energies can be approached in high precision experiments at lower energies. In such experiments one can search for deviations in the behaviour of particles from the predictions within the standard model. Any such deviation would signal New Physics, not yet covered by the standard theory. These experiments can probe New Physics at energy scales far beyond what is reachable for direct particle production at present high energy accelerators and also for those in the foreseeable future. We discuss here selected projects that are conducted with stored and confined particles, ions and atoms (see also [3]).

2. Antiprotons
Experiments on antiprotons and antiprotonic atoms and ions [4, 5] are excellently suited for precise tests of the (i) CPT symmetry, such as in comparisons of particle–antiparticle properties [6–12] and in antihydrogen optical and microwave spectroscopy [13], (ii) tests of elementary physics questions, such as searches for the effects of gravity on antimatter, and (iii) the precise determination of fundamental constants, such as particle masses and charges, magnetic moments and g-factors. Research with antiprotons at low energies is a promising field for the coming decades; a new facility such as the ELENA ring at CERN will reduce the beamtime pressure for the growing community.

The hyperfine structure of antihydrogen is due to contact interaction between its constituents. It is expected to have higher sensitivity to short range new forces rather than the gross structure in this atom. At CERN AD two experiments address the ground state hyperfine splitting in antihydrogen. The ALPHA collaboration has observed a first microwave induced spin flip signal in the antiatom [13]. The ASACUSA collaboration [14] aims for measuring the splitting in a Rabi type apparatus using a beam of antihydrogen [15, 16]. The experiment is rapidly progressing and promises ultimately the best test of CPT, if interpreted in the framework of the standard model extension [17].

Gravity is least understood among the four known fundamental interactions. It is not part of the very successfully confirmed standard model. There is no theoretical approach that rigorously would provide a prediction of the strength of
gravity for antiparticles as compared to particles. This question must be settled experimentally (for a brief summary of the arguments see e.g. [3]). There are presently various experiments underway which aim to measure the antigravity of antiprotonic atoms. The ALPHA collaboration could set a first—still rather weak—limit on antihydrogen gravity by investigating the time dependence of the spatial distribution pattern of antihydrogen decay products. Their results yield a rather moderate limit on the ratio of the gravitational mass to the inertial mass for antihydrogen to be $<110$, and it can be excluded that antihydrogen falls upwards with a gravitational mass $>65$ times its inertial mass [18]. Because of the importance of the issue of antimatter gravity several experiments are on track at the CERN AD [18–21]. We note that the masses of the proton and the antiproton arise not only from the masses of constituent quarks. The gluons are the same in both particles, in particular concerning gravitational interaction. Therefore the question of antimatter gravity is more complex than just a difference in sign for the particle and antiparticle masses and the search experiments must rather be prepared for small differences in the masses of particles and their antiparticles.

3. Parity violation in atoms

Atomic parity violation provides a means to measure electro-weak running (i.e. the size of the weak mixing (Weinberg) angle ($\sin^2 \Theta_W$)) at a low momentum transfer. Atoms and Ions with a well calculable atomic structure, i.e. in particular alkali atoms and alkali Earth ions, and a high nuclear charge $Z$ are favoured for such experiments, because the weak effects scale stronger than $Z^3$. Consequently experiments concentrate on heavy atoms and ions with one electron in the valence shell such as Fr atoms and Ra$^+$ ions [22, 23]. Atoms with more complicated structure, such as e.g. Yb, can have even significantly larger effects; however, atomic structure calculations for such systems are not well enough developed for extracting competitive precise values for, e.g., $(\sin^2 \Theta_W)$. Such systems are better suited for investigating nuclear properties like, e.g., nuclear anapole moments [25].

The atomic parity experiments are time consuming as, next to most accurate theory values for the investigated quantities, highest precision experimental setups are required to reach the sub-% level of precision. For sensitive experiments with, e.g., radioactive species such as Fr and Ra, where although on one hand the interesting weak effects are large [24], on the other hand effective trapping of the isotopes is essential, because of the low number of these radioactive atoms, a profound understanding of the atomic level structure is indispensable. Thus requires a constructive interplay of theorists and experimentalists [26]. For Ra$^+$ a five-fold improvement in the value of the Weinberg angle appears possible for measurements on a single Ra$^+$ ion within one week of measurement time [26].

Recently it has been pointed out that atomic parity experiments, which are capable to extract a competitive value for $\sin^2 \Theta_W$, have also sensitivity to dark $Z$ bosons. It appears that in particular light bosons would shift $\sin^2 \Theta_W$ towards lower (or higher) values, significantly more than for intermediate energies where presently several experiments are ongoing (see e.g. [27]).

Also molecules such as SrF and RaF render the possibility to study weak interaction contributions and in particular to study effects such as nuclear anapole moments [28]. New technology to slow down such systems for such precise measurements is becoming available [29]. For experiments on molecules effective deceleration and trapping appears to be a prerequisite. At the Van Swinderen Institute (VSI) in Groningen experiments are on their way towards such a parity violation measurement using a some 5 m long rf decelerator. First signals of significant molecule slowdown have been already achieved for SrF [29].

4. Permanent electric dipole moments (EDMs)

Permanent EDMs, which would violate both parity (P) and time reversal (T), are presently searched for in a variety of experiments (see, e.g., [30] and references therein). EDM experiments are considered promising approaches to find new sources of CP violation. Such might provide information to explain the matter–antimatter asymmetry in the Universe [12]. EDM experiments can be distinguished by the systems which are expected to carry an EDM. There are experiments searching for an EDM in (i) bare free particles, (ii) atoms, (iii) nuclei and (iv) complex systems like molecules or even condensed matter.

Free particle EDMs are searched for with elementary particles such as muons or with neutrons. The absolute values of such EDM limits are not the smallest established, however, for particular questions they still are the tightest bounds [30]. The search for an EDM in the $^{109}$Hg atom provides the tightest bound of all searches for an EDM at $3.1 \times 10^{-29}$ cm (95% C.L.) [31, 32]. This experiment in a diamagnetic atom, where sensitivity to an electron EDM is suppressed and in first instance a nuclear EDM is searched for, can be interpreted in terms of various limits on CP violating mechanisms.

The modern experiments in atoms, molecules or in ions try to exploit significant enhancement factors of elementary particle EDMs in composed systems. As such enhancement factors for elementary particle EDMs in composed systems can be of order up to $10^6$, new precision experiments in systems such as the molecules YbF [33, 34] and ThO [35] have yielded significant improvements over the previous limits on the electron EDM. The ACME experiment [35] has established a limit of $8.7 \times 10^{-29}$ cm (90% C.L.) for the electron EDM. The experimenters see room for further significantly lowering this bound. A new area is being explored with molecular ions such as HIF stored in rf traps [36] and promises competitive results for the electron EDM.

In this field, control of systematic effects and possible fake signals is the most urgent issue. A particularly interesting possibility to measure a nuclear EDM arises for gas mixtures of $^{3}$He and $^{129}$Xe where the long coherence times promise improvements of up to 4 orders of magnitude over the bound
established for $^{199}$Hg [37]. In nuclei of Rn and Ra levels of opposite parity lie close to each other as a consequence of the observed nuclear octupole deformation (see e.g. [38]). Experiments to search for a nucleon EDM in these atoms are underway and preparation experiments take place (see e.g. [39, 40]).

Progress concerning EDMs in the next years can be expected from such table top experiments primarily, as possible EDM projects with charged systems in storage rings (see, e.g. [41]) are still in an orientation phase. They are primarily concerned with the development of necessary equipment and principal experimental techniques. On the theory side there has been progress in understanding possible mechanisms that can induce EDMs in particular for lighter nuclei [42]. As far as technology for such ring EDM experiments is concerned, the gap of 10 orders of magnitude in sensitivity between what has been achieved with muons and where other approaches have established EDM limits could be narrowed with, e.g., a muon or nuclear EDM experiment in the range of sensitivity of some $10^{-24}$ e cm. Corresponding proposals exist, e.g. for muons [43].

5. Lorentz invariance

Precision tests of Lorentz invariance have been in the core of precision experiments. Enormous activity happened within in the past decade [44]. Since a general framework has been provided through the standard model extension [45, 46] experiments with mind boggling precision could be performed, testing for new physics well beyond the Planck scale. Despite the big success of these experiments, they have one common drawback: they all have tested with highest accuracy only effects in the electromagnetic interaction. Since we know that discrete symmetry violations are only present in weak interactions, we might wonder, whether Lorentz invariance violation might also not be present in electromagnetic interactions. This strongly motivates new experiments on, e.g., weak processes. Those can have a discovery potential already for experiments at much lower levels of precision, since they are exploring a completely new territory. Such dedicated experiments exploiting weak interactions have just been started [47] and theory has developed further into this direction [48].

Among the tests of Lorentz invariance in electromagnetic interactions are spin precession experiments where the free spin precession of polarized $^3$He and $^{129}$Xe in mixed samples (with spin relaxation times of 4–6 h and of more than 60 h, respectively) has been recorded as a function of sidereal time. No effect was found. From this, various Lorentz violating parameters could be limited and a best upper bound of $8.4 \times 10^{-34}$ GeV could be established for neutrons [49].

At the late TRI$\mu$P facility at the AGOR cyclotron in Groningen, NL, Lorentz violation in weak interactions has been tested in the $\beta$-decay $^{20}$Na $\rightarrow ^{20}$Ne + $\beta^+$ + $\gamma$. The $\beta$-decay asymmetry was monitored as a function of the sidereal time. To suppress systematics the polarization was flipped every 4 s and the spatially symmetric $\gamma$-radiation was used as an independent sample monitor. A novel limit on Lorentz violation in weak interactions could be established [47, 50] already in an early measurement campaign and more precise data are being analyzed. The experiments are complemented by theoretical work that enables comparison of various experimentally accessible parameters in a now common framework also for weak processes [51].

6. The new muon g-2 experiment

The muon magnetic anomaly $a_{\mu}$ is a key quantity within the standard model as it provides for an indirect test to New Physics. Its value has been measured to 0.5 ppm at the Brookhaven National Laboratory (BNL), Upton, New York, USA. The anomaly of muons of both possible signs of charge agree at 0.7 ppm [52]. The experimental result and the value calculated within the standard model differ today by some four standard deviations. Whereas the experimental value remained so far unchallenged for almost a decade, the theoretical value has been subject to several in part severe refinements. At this point the theory values obtained along different routes agree well [53].

A new experiment has been started at the Fermi National Accelerator Laboratory (FNAL), Chicago, USA [53]. It uses the same experimental principle as the Brookhaven experiment. In particular the same experimental concept, and most of all crucial pieces of equipment such as the same storage ring magnet and the same magnetic field control concept will be employed again. To this extent the hardware has been moved with significant press coverage and public interest from BNL to FNAL, where a new building has been set up on the new muon campus as the experiment’s hardware new home. For the experiment the detectors and the data acquisition will be upgraded and, in particular, a more intense muon beam with much less contaminations in the particle beam will be used. The experiment aims for half an order of magnitude improvement in $a_{\mu}$ for positive muons, which will essentially be achieved by the higher flux of muons that can be enjoyed at the new site.

At J-PARC a novel experimental approach to measure $a_{\mu}$ is in its R&D phase [54]. The experiment foresees a small diameter storage ring at lower than magic momentum (where the influence of the necessary electric focusing field is canceled). For this experiment largely different systematics will apply compared to the FNAL experiment. Operating below magic momentum, e.g., will make the result very sensitive to electric fields which need to be surveyed and monitored next to the magnetic field. The independent measurement of $a_{\mu}$ will be very important once the experiment at FNAL will have confirmed or not have confirmed the present 4 standard deviation difference between experiment and theory.

Concerning theory, the value of the g-2 result will strongly depend on the general acceptance of the theoretical approach that will be chosen to obtain the hadronic light-by-light scattering contribution to the magnetic anomaly. This value must be calculated based on a valid theoretical model and it cannot be measured directly in an independent way. A
standard model theory value, that will be generally undisputed by the time the experiment will produce a new result, will be crucial for this whole research. A rigorous interpretation of a new muon g-2 experiment will also require better knowledge of the muon magnetic moment $\mu_{\mu}$, which can be obtained, e.g., from an improved measurement of the muonium ground state hyperfine structure splitting. Such an experiment is progressing at J-PARC, Tokai, Japan [55].

7. Conclusions

The precision values obtained in the measurements discussed here form a robust backbone that can serve as a reference system against which all searches for new physics must be held in order to decide whether new physics may have been found. Any precisely measured value of any physical quantity is always an important piece in the puzzle in its own right. Preferences which of the presently ongoing experiments would have higher potential to find New Physics or to point out new directions could not be based on any unbiased knowledge.

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References

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