Fundamental Symmetries and Interactions
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In nuclear physics numerous possibilities exist to investigate fundamental symmetries and interactions. In particular, the precise measurements of properties of fundamental fermions, searches for new interactions in β-decays, and violations of discrete symmetries offer possibilities to search for physics beyond standard theory. Precise measurements of fundamental constants can be carried out. Low energy experiments allow to probe New Physics at mass scales far beyond the reach of present accelerators or such planned for the future and at which predicted new particles could be produced directly.

1. Fundamental Forces and Symmetries

Symmetries play an important and crucial role in physics. Global symmetries give rise to conservation laws and local symmetries yield forces [1]. To date we know four fundamental interactions: (i) Electromagnetism, (ii) Weak Interactions, (iii) Strong Interactions, and (iv) Gravitation. These four forces are fundamental in the sense that all observed dynamical processes in physics can be traced back to one or a combination of them. Together with fundamental symmetries they form a framework on which all physical descriptions ultimately rest.

The Standard Model (SM) is a remarkable theory which allows that Electromagnetic, Weak and many aspects of Strong Interactions can be described to astounding precision in one single coherent picture. It is a major goal in modern physics to find a unified quantum field theory which includes all the four known fundamental forces in physics. On this way, a satisfactory quantum description of gravity remains yet to be found and is a lively field of actual activity.

In this article we are concerned with important implications of the SM and centrally with searches for new, yet unobserved interactions. Such are suggested by a variety of speculative models in which extensions to the present standard theory are introduced in order to explain some of the not well understood and not well founded features in the SM. Among the intriguing questions in modern physics are the hierarchy of the fundamental fermion masses and the number of fundamental particle generations. Further, the electroweak SM has a rather large number of some 27 free parameters. All of them need to be extracted from experiments. It is rather unsatisfactory that the physical origin of the observed breaking of discrete symmetries in weak interactions, e.g. of parity (P), of time reversal (T) and of combined charge conjugation and parity (CP), remains unrevealed, although the experimental findings can be well described within the SM.
The speculative models beyond the present standard theory include such which involve left-right symmetry, fundamental fermion compositeness, new particles, leptoquarks, supersymmetry, supergravity and many more. Interesting candidates for an all encompassing quantum field theory are string or membrane (M) theories which in their low energy limit may include supersymmetry.

In the field of fundamental interactions there are two important lines of activities: Firstly, there are searches for physics beyond the SM in order to base the description of all physical processes on a conceptually more satisfying foundation, and, secondly, the application of solid knowledge in the SM for extracting fundamental quantities and achieving a description of more complex physical systems, such as atomic nuclei. Both these central goals can be achieved at upgraded present and novel, yet to be built facilities. In this connection a high intensity proton driver would serve to allow novel and more precise measurements in a large number of actual and urgent issues in this field [2].

Here we can only address a few aspects of a rich spectrum of possibilities.

2. Fundamental Fermions

The Standard Model has three generations of fundamental fermions which fall into two groups, leptons and quarks. The latter are the building blocks of hadrons and in particular of baryons, e.g. protons and neutrons, which consist of three quarks each. Forces are mediated by bosons: the photon, the \( W^\pm \) and \( Z^0 \)-bosons, and eight gluons.

2.1. Neutrinos

The leptons do not take part in strong interactions. In the SM there are three charged leptons \((e^-, \mu^-, \tau^-)\) and three electrically neutral neutrinos \((\nu_e, \nu_\mu, \nu_\tau)\) as well as their respective antiparticles. For the neutrinos eigenstates of mass \((\nu_1, \nu_2, \nu_3)\) and flavour are different and connected through a mixing matrix analogous to the Cabbibo-Kobayashi-Maskawa mixing in the quark sector (see 2.2). The reported evidence for neutrino oscillations strongly indicate finite \(\nu\) masses. Among the recent discoveries are the surprisingly large mixing angles \(\Theta_{12}\) and \(\Theta_{23}\) (see [3, 4]). The mixing angle \(\Theta_{13}\), the phases for CP-violation, the question whether \(\nu\)'s are Dirac or Majorana particles and a direct measurement of a neutrino mass rank among the top issues in neutrino physics.

2.1.1. Neutrino Oscillations

The recent developments in the field of neutrino oscillation research and evidence for such from solar, reactor, atmospheric and accelerator neutrino experiments are reviewed in [3] and [4] in this volume.

2.1.2. Novel Ideas in the Neutrino Field

Two new and unconventional neutrino detector ideas have come up and gained support in the recent couple of years, which have a potential to contribute significantly towards solving major puzzling questions in physics.

(i) The first concept employs the detection of high energetic charged particles originating from neutrino reactions through Cherenkov radiation in the microwave region (or even sound waves), which results, if such particles interact with, e.g., the Antarctic ice or the salt in large salt domes as they can be found also in the middle of
A new concept of a direction sensitive neutrino detection for low energy antineutrinos offers not only progress in traditional neutrino research areas like neutrino oscillation, neutrino scattering and supernova watching, but also for tomography of the earth to find out about the distribution of radionuclides in the earth’s crust, mantle and core. The directional sensitivity of this novel detector principle makes it particularly interesting for measuring the yet unknown neutrino generation mixing angle $\Theta_{13}$ in a combined near/far detector reactor experiment.

Europe. One advantage of such a detector is its larger density as compared to water, the typical detector material used up to date. It remains to be verified whether this concept will also be applicable for high energetic accelerator neutrinos, if timing information and narrowband radio detection techniques will be employed.

(ii) The second concept allows directional sensitivity for low energy anti-neutrinos. The reaction $\bar{\nu} + p \rightarrow e^+ + n$ has a 1.8 eV threshold. The resulting neutron (n) carries directional information in its angular distribution after the event. In typical organic material the neutron has a range $r_n$ of a few cm. With a detector consisting of tubes with a diameter of order $r_n$ and with, e.g., boronated walls the resulting alpha-particle from the n+B nuclear reaction can be used to determine on average the direction of incoming anti-neutrinos. Such a detector (Fig. 2.1.1), if scaled to sufficient mass, can be used to determine the distribution of radionuclides in the interior of the earth (including testing rather exotic ideas like the existence of a nuclear reactor in the earth’s core). A further rather promising application would be a measurement of the neutrino generation mixing angle $\Theta_{13}$ in a reactor experiment with a near and far detector in $\approx$ few 100 m and $\approx$ few 100 km distance. For this measurement the importance of directional sensitivity for low energy $\nu$’s is an indispensable requirement.

2.1.3. Neutrino Masses

The best neutrino mass limits result from measurements of the tritium $\beta$-decay spectrum close to its endpoint. Since neutrinos are very light particles, a mass measurement can best be performed in this region of the spectrum as in other parts the nonlinear dependencies caused by the relativistic nature of the kinematic problem cause a significant loss of accuracy which overwhelms the gain in statistics one could hope for. Two
groups in Troitzk and Mainz used spectrometers based on Magnetic Adiabatic Collimation combined with an Electrostatic filter (MAC-E technique) and found $m(\nu_e) < 2.2 \text{ eV}$ \cite{7, 8}.

A new experiment, KATRIN \cite{9}, is presently prepared in Karlsruhe, Germany, which is planned to exploit the same technique (Fig. 2.1.3). It aims for an improvement by about one order of magnitude. The physical dimensions of a MAC-E device scale inversely with the possible sensitivity to a finite neutrino mass. This may ultimately limit an approach with this principle.

The KATRIN experiment will be sensitive to the mass range where a finite effective neutrino mass value of between 0.1 and 0.9 eV was extracted from a signal in neutrinoless double $\beta$-decay in $^{76}$Ge \cite{10}. The Heidelberg-Moskow collaboration performing the Ge experiment in the Grand Sasso laboratory in Italy reports a 4.2 standard deviation effect for the existence of this decay \cite{11}. It should be noted that neutrinoless double $\beta$-decay is only possible for Majorana neutrinos. Therefore a confirmed signal would solve one of the most urgent questions in particle physics.

Figure 2. The KATRIN neutrino experiment aims for measuring a neutrino mass directly in a MAC-E spectrometer \cite{8}.

2.2. Quarks - Unitarity of Cabbibo-Kobayashi-Maskawa-Matrix

The mass and weak eigenstates of the six quarks (u,d,s,c,b,t) are different and related to each other by a $3 \times 3$ unitary matrix, the Cabbibo-Kobayashi-Maskawa (CKM) matrix (Table 1). Non-unitarity of this matrix would be an indication of physics beyond the SM and could be caused by a variety of possibilities, including the existence of more than three quark generations or yet undiscovered muon decay channels. The unitarity of the CKM matrix is therefore a severe check on the validity of the standard theory and sets bounds on speculative extensions to it.

The best test of unitarity results from the first row of the CKM matrix through

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta$$,

(1)
Figure 3. Uncertainties for three different methods to determine $V_{ud}$: nuclear $\beta$-decays, neutron decays and pion $\beta$-decay. $\delta_R$ is the transition dependent part and $\Delta_R$ is the transition independent part of the radiative correction. For nuclear $\beta$-decay there is a radiative correction $\delta_{NS}$ from nuclear structure. The arrow indicates the estimated range of the total uncertainty, mainly arising from difficulties assigned by the Particle Data Group to calculations of the structure-dependent isospin breaking correction $\delta_C$.

where the SM predicts $\Delta$ to be zero. The size of the known elements determine that with the present uncertainties only the elements $V_{ud}$ and $V_{us}$ play a role. $V_{ud}$ can be extracted with best accuracy from the fit values of superallowed $\beta$-decays. Other possibilities are the neutron decay and the pion $\beta$-decay, which both are presently studied (Fig. 3).

$V_{us}$ can be extracted from K decays and in principle also from hyperon decays. The Particle Data Group [12] had decided to increase the uncertainty of $V_{ud}$ from nuclear $\beta$-decay [13] based on their feelings that nuclei would be too complicated objects to trust theory. Interestingly, their own evaluation of $V_{us}$ based on Particle Data Group fits of K-decay branching ratios turned out to be not in accordance with recent independent direct measurements. As a result of the earlier too optimistic error estimates in this part a large activity to test the unitarity of the CKM matrix took off, because a between 2 and 3 standard deviation from unitarity had been persistent. Recent careful analysis of the overall subject has also revealed overlooked inconsistencies in the overall picture [14, 15] and at this time new determinations of $V_{us}$ confirm together with $V_{ud}$ from nuclear $\beta$-decay that $\Delta = 0$ and therewith the unitarity of the CKM matrix up to presently possible accuracy (Fig. 4).
Figure 4. The value of the CKM-matrixelement $V_{us}$ for various determinations. Recent results from several activities in theory and experiment have shown the Particle Data Group value for $V_{us}$ to be significantly wrong, due to wrong fit results for $K$ decay branching ratios. It appears that together with the precise results from nuclear $\beta$-decays the unitarity condition is satisfactorily fulfilled [14].

Table 1

| $V_{ud}$ | $V_{cd}$ | $V_{td}$ | $V_{us}$ | $V_{cs}$ | $V_{ts}$ | $V_{ub}$ | $V_{cb}$ | $V_{tb}$ |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0.9735 to 0.9745 | 0.219 to 0.226 | 0.004 to 0.014 | 0.2208 to 0.2289 | 0.9732 to 0.9748 | 0.037 to 0.044 | 0.0025 to 0.0048 | 0.038 to 0.044 | 0.9990 to 0.9993 |

Because of the cleanest and therefore most accurate theory pion $\beta$-decay (Fig. 3) offers for future higher precision measurements the best opportunities, in principle. The estimate [16] for accuracy improvement from nuclear $\beta$-decays is about a factor 2. The main difficulty for new round rests therefore primarily with finding an experimental technique to obtain sufficient experimental accuracy for pion $\beta$-decay.

2.3. Rare Decays

In the SM baryon number (B) and lepton number conservation reflect accidental symmetries. A total lepton number (L) and a lepton number for the different flavours exists and different conservation laws were experimentally established. Some of these schemes are additive, some obey multiplicative, i.e. parity-like, rules.

Based on a suggestion by Lee and Yang in 1955 [1] there is a strong believe in modern physics that a strict conservation of these numbers remains without a foundation unless they can be associated with a local gauge invariance and with new long-distance interactions.
interactions which are excluded by experiments. Since no symmetry related to lepton numbers could be revealed in the SM, the observed conservation laws remain without status in physics. However, the conservation of the quantity (B-L) is required in the SM for anomaly cancellation. Baryon number, lepton number or lepton flavour violation appear natural in many of the speculative models beyond the SM. Often they allow probabilities reaching up to the present established limits (Table 2).

### 2.3.1. Lepton Number and Lepton Flavour

The observations of the neutrino-oscillation experiments have demonstrated that lepton flavour is broken and only the total additive lepton number has remained unchallenged. Searches for charged lepton flavour violation are practically not affected in their discovery potential by these neutrino results. For example, in a SM with massive neutrinos the induced effect of neutrino oscillation into the branching probability $P_{\mu \rightarrow e\gamma}$ of the possible decay mode $\mu \rightarrow e\gamma$ is of order [19]

$$P_{\mu \rightarrow e\gamma} = \frac{\Delta m_{\nu_1}^2 - \Delta m_{\nu_2}^2}{400 eV^2} \cdot 10^{-39}.$$  \hspace{1cm} (2)$$

This can be completely neglected in view of present experimental possibilities. Therefore we have a clean possibility to search for New Physics at mass scales far beyond the reach of present accelerators or such planned for the future and at which predicted new particles could be produced directly. The rich spectrum of possibilities is summarized in Table 2 and the history and future possibilities for lepton flavour and lepton number violating processes is illustrated in Figure 5. The future projections depend strongly on the availability of a new intense source of particles such as expected from a facility with a high power ($\geq$ MW beam power) proton driver.
Figure 5. Dedicated searches for lepton number and lepton flavour violating processes involving muons (µ) and kaons (K). Recent K experiments and µ⁺e⁻ – µ⁻e⁺ conversion show the most significant gain in sensitivity. The steady increase in sensitivity is due to both improvements in experimental techniques and in the available particle fluxes at accelerators. Projections of possibilities of ongoing activities by their experimenters as well as those of a CERN working group \[17\] for a neutrino factory (NUFACT, 4MW proton driver) are shown.

2.3.2. Baryon Number Violation

Generally, in most models which aim for the Grand Unification of all forces in nature baryon number is not conserved. This has lead over the past two decades to extensive searches for proton decays into various channels. Present large neutrino experiments have in part emerged form proton decay searches and such detectors are well suited to perform these searches along with neutrino detection. Up to now numerous decay modes have been investigated and partial lifetime limits could be established up to $10^{33}$ years. These efforts will be continued with existing setups over the next decade and the detectors with the largest mass have highest sensitivity.

An oscillation between the neutron and its antiparticle (n-\(\bar{n}\)) would violate baryon number by two units \[18\]. Two in principle different approaches have been employed in the latest experiments. Firstly, such searches were performed in the large neutrino detectors, where an oscillation occurring with neutrons within the nuclei of the detector’s material could have been observed as a neutron annihilation signal in which 2 GeV energy are released in form of pions. Secondly, at ILL a beam of free neutrons was utilized. A suppression of an oscillation due to the lifting of the energetic degeneracy between n and \(\pi\) was avoided by a magnetically well shielded conversion channel. Both methods have
established a limit of $1.2 \times 10^8$ s for the oscillation time. Significantly improved limits are expected to emerge from experiments at new intense ultra-cold neutron sources.

3. Discrete Symmetries

3.1. Parity

The observation of neutral currents together with the observation of parity non-conservation in atoms were important to verify the validity of the SM. The fact that physics over 10 orders in momentum transfer - from atoms to highest energy scattering - yields the same electro-weak parameters may be viewed as one of the biggest successes in physics to date.

However, at the level of highest precision electro-weak experiments questions arose, which ultimately may call for a refinement. The predicted running of the weak mixing angle $\sin^2 \theta_W$ (Fig. 6) appears not to be in agreement with observations [20]. If the value of $\sin^2 \theta_W$ is fixed at the $Z^0$-pole, deep inelastic electron scattering at several GeV appears to yield a considerably higher value. A reported disagreement from atomic parity violation in Cs has disappeared after a revision of atomic theory.

A new round of experiments is being started with the $Q_{weak}$ experiment [21] at the Jefferson Laboratory in the USA. For atomic parity violation in principle higher experimental accuracy will be possible from experiments using Fr isotopes or single Ba or Ra

Figure 6. The running of the weak mixing angle $\sin \theta_W$ with energy as predicted by theory [20] is not completely reproduced by experiments. Deep inelastic scattering experiments appear to show a higher value than predicted. Future planned experiments to clarify the situation are indicated with their expected sensitivity.
ions in radiofrequency traps \cite{22}. Although the weak effects are larger in these systems due to their high power dependence on the nuclear charge, this can only be exploited after better atomic wave function calculations will be available, as the observation is always through an interference of weak with electromagnetic effects.

3.2. Time Reversal and CP Violation

The role of a violation of combined charge conjugation (C) and parity (P) is of particular importance through its possible relation to the observed matter-antimatter asymmetry in the universe. This connection is one of the strong motivations to search for yet unknown sources of CP violation. A. Sakharov \cite{23} has suggested that the observed dominance of matter could be explained via CP-violation in the early universe in a state of thermal non-equilibrium and with baryon number violating processes. CP violation as described in the SM is insufficient to satisfy the needs of this elegant model. Permanent Electric Dipole Moments (EDMs) certain correlation observables in $\beta$-decays offer excellent opportunities to find new sources of CP-violation.

3.2.1. Permanent Electric Dipole Moments (EDMs)

A permanent electric dipole moment of any fundamental particle violates both parity and time reversal (T) symmetries. With the assumption of CPT invariance a permanent dipole moment also violates CP. Permanent electric dipole moments for all particles are caused by CP violation as it is known from the K systems through higher order loops. These are at least 4 orders of magnitude below the present experimentally established limits. Indeed, a large number of speculative models foresees permanent electric dipole moments which could be as large as the present experimental limits just allow. Historically the non-observation of permanent electric dipole moments has ruled out more speculative models than any other experimental approach in all of particle physics \cite{24}.

Table 3

The best limits on permanent electric dipole moments.

| Particle | Limit/Measurement (e-cm) | Method |
|----------|--------------------------|--------|
| e        | $< 1.6 \times 10^{-27}$  | Thallium beam \cite{27} |
| $\mu$    | $< 2.8 \times 10^{-19}$  | Tilt of precession plane in magnetic moment experiment \cite{28} |
| $\tau$   | $(-2.2 < d_{\tau} < 4.5) \times 10^{-17}$ | BELLE $e^+e^- \rightarrow \tau\tau$ events \cite{29} |
| n        | $< 6.3 \times 10^{-26}$  | Ultra-cold neutrons \cite{30} |
| p        | $(-3.7 \pm 6.3) \times 10^{-23}$ | 120kHz thallium spin resonance \cite{31} |
| $\Lambda$| $(-3.0 \pm 7.4) \times 10^{-17}$ | Tilt of precession plane in magnetic moment experiment \cite{32} |
| $\nu_e,\mu$ | $< 2 \times 10^{-21}$  | Inferred from magnetic moment limits \cite{33} |
| $\nu_\tau$ | $< 5.2 \times 10^{-17}$  | Z decay width \cite{34} |
| Hg-atom  | $< 2.1 \times 10^{-28}$  | mercury atom spin precession \cite{35} |

Permanent electric dipole moments have been searched for in various systems with different sensitivities (Table 3). In composed systems such as molecules or atoms fundamental particle dipole moments of constituents may be significantly enhanced\cite{25}. Particularly in polarizable systems there can exist large internal fields.

There is no preferred system to search for an EDM. In fact, many systems need to be examined, because depending on the underlying process different systems have in
general quite significantly different susceptibility to acquire an EDM through a particular mechanism. In fact, one needs to investigate different systems. An EDM may be found an "intrinsic property" of an elementary particle as we know them, because the underlying mechanism is not accessible at present. However, it can also arise from CP-odd forces between the constituents under observation, e.g. between nucleons in nuclei or between nuclei and electrons. Such EDMs could be much higher than such expected for elementary particles originating within the popular, usually considered standard theory models. No other constraints are known.

In this active field of research we had recently a number of novel developments. One of them concerns the Ra atom, which has rather close lying $7s7p^3P_1$ and $7s6d^3D_2$ states (Fig. 7). Because they are of opposite parity, a significant enhancement has been predicted for an electron EDM [26], much higher than for any other atomic system. Furthermore, many Ra isotopes are in a region where (dynamic) octupole deformation occurs for the nuclei, which also may enhance the effect of a nucleon EDM substantially, i.e. by some two orders of magnitude. From a technical point of view the Ra atomic levels of interest for an experiment are well accessible spectroscopically and a variety of isotopes can be produced in nuclear reactions. The advantage of an accelerator based Ra experiment is apparent, because EDMs require isotopes with spin and all Ra isotopes with finite nuclear spin are relatively short-lived [44].

A very novel idea was introduced for measuring an EDM of charged particles. In this method the high motional electric field is exploited, which charged particles at relativistic speeds experience in a magnetic storage ring. (Fig. 8a). In such an experiment the Schiff
Theorem can be circumvented (which had excluded charged particles from experiments because of the Lorentz force acceleration) because of the non-trivial geometry of the problem [25]. With an additional radial electric field in the storage region the spin precession due to the magnetic moment anomaly can be compensated, if the effective magnetic anomaly $a_{\text{eff}}$ is small, i.e. $a_{\text{eff}} \ll 1$. The method was first considered for muons. For longitudinally polarized muons injected into the ring an EDM would express itself as a spin rotation out of the orbital plane (Fig. 8b). This can be observed as a time dependent (to first order linear in time) change of the above/below the plane of orbit counting rate ratio. For the possible muon beams at the future J-PARC facility in Japan a sensitivity of $10^{-24}$ e cm is expected [37]. In such an experiment the possible muon flux is a major limitation. For models with nonlinear mass scaling of EDM’s such an experiment would already be more sensitive to certain new physics models than the present limit on the electron EDM [38]. An experiment carried out at a more intense muon source could provide a significantly more sensitive probe to CP violation in the second generation of particles without strangeness.

The deuteron is the simplest known nucleus. Here an EDM could arise not only from a proton or a neutron EDM, but also from CP-odd nuclear forces. It was shown very recently [40] that the deuteron can be in certain scenarios significantly more sensitive than the neutron. In equation (3) this situation is evident for the case of quark chromo-EDMs:

\[
\begin{align*}
    d_p &= -4.67 \, d_c^p + 5.22 \, d_u^p, \\
    d_n &= -0.01 \, d_c^n + 0.49 \, d_u^n.
\end{align*}
\]

(3) It should be noted that because of its rather small magnetic anomaly the deuteron is a particularly interesting candidate for a ring EDM experiment and a proposal with a sensitivity of $10^{-27}$ e cm exists [39]. In this case scattering off a target will be used to
observe a spin precession. As possible sites of an experiment the Brookhaven National Laboratory (USA), the Indiana University Cyclotron Facility (USA) and the Kernfysisch Versneller Instituut (Netherlands) are considered.

3.2.2. Correlations in $\beta$-decays

In standard theory the structure of weak interactions is V-A, which means there are vector (V) and axial-vector (A) currents with opposite relative sign causing a left handed structure of the interaction and parity violation [41]. Other possibilities like scalar, pseudo-scalar and tensor type interactions which might be possible would be clear signatures of new physics. So far they have been searched for without positive result. However, the bounds on parameters are not very tight and leave room for various speculative possibilities. The double differential decay probability $d^2W/d\Omega_e d\Omega_\nu$ for a $\beta$-radioactive nucleus is related to the electron and neutrino momenta $\vec{p}$ and $\vec{q}$ through

$$\frac{d^2W}{d\Omega_e d\Omega_\nu} \sim 1 + a \frac{\vec{p} \cdot \vec{q}}{E} + b \sqrt{1 - (Z\alpha)^2} \frac{m_e}{E} \left[ A \frac{\vec{p}}{E} + B \frac{\vec{q}}{E} + D \frac{\vec{p} \times \vec{q}}{E} \right]$$

$$+ < \vec{J} > \left[ G \frac{\vec{p}}{E} + Q \vec{J} + R < \vec{J} > \times \vec{q} \right]$$

(4)

where $m_e$ is the $\beta$-particle mass, $E$ its energy, $\vec{\sigma}$ its spin, and $\vec{J}$ is the spin of the decaying nucleus. The coefficients D and R are studied in a number of experiments at this time and they are T violating in nature. Here D is of particular interest for further restricting model parameters. It describes the correlation between the neutrino and $\beta$-particle momentum vectors for spin polarized nuclei. The coefficient R is highly sensitive within a smaller set of speculative models, since in this region there exist some already well established constraints, e.g., from searches for permanent electric dipole moments [41].

From the experimental point of view, an efficient direct measurement of the neutrino momentum is not possible. The recoiling nucleus can be detected instead and the neutrino momentum can be reconstructed using the kinematics of the process. Since the recoil nuclei have typical energies in the few 10 eV range, precise measurements can only be performed, if the decaying isotopes are suspended using extreme shallow potential wells. Such exist, for example, in magneto-optical traps, where many atomic species can be stored at temperatures below 1 mK.

Such research is being performed at a number of laboratories worldwide. At the Kernfysisch Versneller Instituut (KVI) in Groningen a new facility is being set up, in which T-violation research will be a central scientific issue [44, 45]. At this new facility the isotopes of primary interest are $^{20,21}$Na and $^{18,19}$Ne. These atoms have suitable spectral lines for optical trapping and since also the nuclear properties are such that rather clean transitions can be observed.

A recent measurement at Berkeley, USA, the asymmetry parameter $a$ in the $\beta$-decay of $^{21}$Na has been measured in optically trapped atoms [42]. The value differs from the present SM value by about 3 standard deviations. Whether this is an indication of new physics reflected in new interactions in $\beta$-decay, this depends strongly on the
\( \beta/(\beta + \gamma) \) decay branching ratio for which some 5 measurements exists which in part disagree significantly [13]. New measurements are needed.

4. Properties of Known Basic Interactions

4.1. Electromagnetism and Fundamental Constants

In the electro-weak part of the SM very high precision can be achieved for calculations, in particular within Quantum Electrodynamics (QED), which is the best tested field theory we know and a key element of the SM. QED allows for extracting accurate values of important fundamental constants from high precision experiments on free particles and light bound systems, where perturbative approaches work very well for their theoretical description. Examples are the fine structure constant \( \alpha \) or the Rydberg constant \( R_\infty \). The obtained numbers are needed to describe the known interactions precisely. Furthermore, accurate calculations provide a basis to searches for deviations from SM predictions. Such differences would reveal clear and undisputed signs of New Physics and hints for the validity of speculative extensions to the SM. For bound systems containing nuclei with high electric charges QED resembles a field theory with strong coupling and new theoretical methods are needed.

4.1.1. Muonium and Muon Magnetic Anomaly

The interpretation of measurements in the muonium atom, the bound state of a \( \mu^+ \) and an \( e^- \), is free of difficulties arising from the structure of its constituents [17]. Thus QED predictions with two orders of magnitude higher accuracy than for the hydrogen atom are possible. The ground state hyperfine splitting as well as the \( 1s - 2s \) energy difference have been precisely determined recently. These measurements can be interpreted as QED tests or alternatively -assuming the validity of QED- as independent measurements of \( \alpha \) as well as of muon properties (muon mass \( m_\mu \) and muon magnetic moment \( \mu_\mu \)). These experiments are statistics limited. Significantly improved values would be possible at new intense muon sources. There is a close connection between muonium spectroscopy and a measurement of the muon magnetic anomaly \( a_\mu \), the relative deviation of the muon g-factor from the Dirac value 2. Muonium spectroscopy provides fundamental muon constants, such as its mass, electric charge and magnetic moment.

Precise values of these fundamental constants are indispensable for the evaluation of the experimental results of a muon g-2 measurement series in a magnetic storage ring (Fig. 9) at the Brookhaven National Laboratory [18]. The muon magnetic anomaly arises from quantum effects and is mostly due to QED. Further, there is a contribution from strong interactions of 58 ppm which arises from hadronic vacuum polarization. The influence of weak interactions amounts to 1.3 ppm. Whereas QED and weak effects can be calculated from first principles, the hadronic contribution needs to be evaluated through a dispersion relation and experimental input from \( e^+ - e^- \) annihilation into hadrons (up to now in the essential region from the CMD experiment in Novosibirsk, Russia) or hadronic \( \tau \)-decays. Calculations of the hadronic part in \( a_\mu \) depend on the choice of presently available experimental hadronic data. The results for \( a_\mu \) differ by 3.0 respectively 1.6 standard deviations from the averaged experimental value. Intense theoretical and experimental efforts are needed to solve the hadronic correction puzzle. The available new data on \( e^+ - e^- \) annihilation from the KLOE experiment in Frascati, Italy, appear to confirm earlier
Figure 9. The g-2 storage ring at the Brookhaven National Laboratory [48].

measurements [49]. For the muon magnetic anomaly improvements both in theory and experiment are required, before a definite conclusion can be drawn whether a hint of physics beyond standard theory [50] has been seen. A continuation of the g-2 experiment with improved equipment and beams was scientifically approved in 2004.

4.1.2. Muonic Hydrogen and Proton Radius

A measurement of the proton mean square charge radius $r_p$ is underway at PSI [51]. The experiment aims for a determination of the classical Lambshift in the n=2 state with laser spectroscopy. The transition is within reach of infrared laser radiation. Muonic hydrogen has a higher sensitivity to proton properties compared to natural hydrogen owing to the about 200 times smaller Bohr radius of the system and the associated higher overlap probability of the muon with the proton (as compared to the electron in natural hydrogen). One expects a significant improvement in the knowledge of $r_p$ over the value available from high precision laser spectroscopy in the 1s-2s transition in natural hydrogen.

4.1.3. Does $\alpha_{QED}$ Vary with Time?

The question whether fundamental constants are stable in time goes back to the large number hypothesis of Dirac. More recently reports came out, in which evidence for a time variation of the fine structure constant $\alpha_{QED}$ was reported from astronomical observations. Absorption of quasar light in interstellar media was employed to search for shifts in atomic fine structure lines. Due to relativistic effects, some atomic levels would shift positive and some others would simultaneously shift negative, if $\alpha_{QED}$ would vary [52]. A variation of $\dot{\alpha}/\alpha = (6.40 \pm 1.35) \times 10^{-16}$ yr$^{-1}$ is observed by one collaboration [53]. However, this could
not be confirmed by a second group working with the same astronomical instruments [54] and by laboratory experiments using the narrow atomic hydrogen 1s-2s transition in a comparison with an atomic clock [55]. Further work to clarify the situation in this lively subfield will be needed.

4.2. Quantum Chromodynamics (QCD)

At PSI spectroscopy of atomic x-rays from pionic hydrogen allows to determine a Strong Interaction shift and broadening of atomic transitions. For the chosen 3p-1s transition the shift and broadening are predominantly due to the 1s state. The measurement yields the pion-nucleon scattering length with very good precision [56] and therefore presents a high precision test of chiral perturbation theory, a powerful low energy approach in QCD.

Figure 10. Limits on non-Newtonian gravity. The strength $|\alpha|$ as a function of the the Yukawa length scale. The parameter space was further limited by a neutron gravitation interferometer [58].

4.3. Gravity

String and M theories try to find a common description of gravity and quantum mechanics. In their context appear predictions of extra dimensions which could manifest
Table 4: Research areas and typical experiments where a high power proton driver is indicated for significant progress [59]. The necessary typical proton beam energy is given. A beam power of about 4 MW is assumed. Most experiments would benefit from a pulsed time structure of the beam.

| Research Field | Physics Question addressed | Method | Comments | ≈ 1 GeV | ≈ 30 GeV |
|----------------|----------------------------|--------|----------|---------|----------|
| nature of neutrinos | oscillations, CP violation masses | long baseline | novel detectors? Salt domes? | × | × |
|                  |                            | spectrometer | only $\nu_\mu$ | – | × |
| T and CP violation | permanent electric dipole moments; D (R) coefficients in $\beta$-decays; $D^0$-decays | spin precession in electric fields; trapping of radioactive atoms; spectrometer | novel method using storage rings Radium atoms; stored radioactive atoms; | × | × |
| rare and forbidden decays | n-$\pi$ conversion | dedicated | ultracold n’s | × | |
|                  | M-$\overline{M}$ conversion | spectrometers | novel method, unique potential | × | |
|                  | $\mu \rightarrow e\gamma$ | | unique potential | × | |
|                  | $\mu \rightarrow 3e$ | | unique potential | × | |
|                  | $\mu N \rightarrow eN$ | | unique potential | × | |
| Correlations in $\beta$-decays | non V-A in $\beta$-decay | radioactive | optically trapped | × | × |
|                  | $\mu N \rightarrow eN$ | nuclear decays | radioactive isotopes | × | × |
| unitarity of CKM matrix | n-decay | lifetimes | large potential | × | |
|                  | $pi-\beta$-decay | and | to test SM | × | |
|                  | $K$-decays | transition probabilities | in new precision round | – | × |
| CPT conservation | nuclei | sidereal variations | interaction based | × | |
|                  | $p, \overline{p}$ | of spin dependent quantities; particle-antiparticle properties | models needed | – | × |
|                  | $\mu$ | | | × | × |
themselves in deviations from the Newtonian laws of gravity at small distances. Therefore an number of searches for such large extra dimensions has been started. At the Institute Laue langevain in Grenoble, France, a new limit in parameter space (Fig. 10) has been established for extra forces of the type

\[ V(r) = G \frac{m_1 \cdot m_2}{r} (1 + \alpha \cdot \exp\left(\frac{-r}{\lambda}\right)), \]  

where \( \alpha \) determines the strength and \( \lambda \) is the Yukawa range of the additional interaction. The experiment uses quantum mechanical interference patterns from ultra-cold neutrons which may be viewed as gravitational matter "standing" waves [57].

5. New Instrumentation Needed

Progress in the field of low energy experiments to verify and test the SM and to search for extensions to it would benefit in many cases significantly from new instrumentation and a new generation of particle sources. In particular, a high power proton driver would boost a large number of possible experiments which all have a high and robust discovery potential [2]. In Table 3 two possible scenarios for a 1 GeV and a 30 GeV machine are compared. The availability of such a machine would be desirable for a number of other fields as well, such as neutron scattering, in particular ultra-cold neutron research, or a new ISOL facility (e.g. EURISOL) for nuclear physics with nuclei far off the valley of stability. A joint effort of several communities could benefit from synergy effects. Possibilities for such a machine could arise at CERN [59, 17], FEMILAB, J-PARC and GSI with either a high power linac or a true rapid cycling synchrotron.

6. Conclusions

Nuclear physics and nuclear techniques offer a variety of possibilities to investigate fundamental symmetries in physics and to search for physics beyond the SM. Experiments at Nuclear Physics facilities at low and intermediate energies offer in this respect a variety of possibilities which are complementary to approaches in High Energy physics and in some cases exceed those significantly in their potential to steer physical model building.

The advantage of high particle fluxes at a Multi-Megawatt facility allow higher sensitivity to rare processes because of higher statistics and because also in part novel experimental approaches are enabled by the combination of particle number and an appropriate time structure of the beam. The field is looking forward to a rich future.

7. Acknowledgments

The author would like to the members of the NuPECC Long Range Plan 2004 Fundamental Interaction working group [2] for numerous fruitful discussions. This work was supported in part by the Dutch Stichting voor Fundamenteel Onderzoek der Materie (FOM) in the framework of the TRIMUP programme.

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