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Fundamental symmetries and interactions —Some aspects

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Abstract. In the framework of nuclear physics and at nuclear physics facilities a large number of different experiments can be performed which render the possibility to investigate fundamental symmetries and interactions in nature. In particular, the precise measurements of properties of fundamental fermions, searches for new interactions in β-decays, and violations of discrete symmetries have a robust discovery potential for physics beyond standard theory. Precise measurements of fundamental constants can be carried out as well. Low energy experiments allow probing of New Physics models at mass scales far beyond the reach of present accelerators or such planned for the future in the domain of high energy physics and at which predicted new particles could be produced directly.

PACS. 11.30.-j Symmetry and conservation laws – 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries – 06.20.Jr Determination of fundamental constants

1 Introduction

Symmetries play an important and central role in physics. Whereas global symmetries relate to conservation laws, local symmetries yield forces [1]. Today four fundamental interactions are known in physics: i) Electromagnetism, ii) Weak Interactions, iii) Strong Interactions, and iv) Gravitation. These forces are considered fundamental, because all observed dynamic processes in nature can be traced back to one or a combination of them. Together with fundamental symmetries they from the framework on which all physical descriptions ultimately rest.

The Standard Model (SM) is a most remarkable theory. 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. To achieve this, a satisfactory quantum description of gravity remains yet to be found. This is a lively field of actual activity.

In this write-up we are concerned with important implications of the SM. In particular, searches for new, yet unobserved interactions play a central role. At present, 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 features in the SM, which are not well understood and not well founded, although the corresponding experimental facts are accurately described. Among the intriguing questions in modern physics are the number of fundamental particle generations and the hierarchy of the fundamental fermion masses. In addition, the electro-weak SM has a rather large number of some 27 free parameters [2], which all 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. Without secure future experimental evidence all of these speculative theories will remain without status in physics, independent of the mathematical elegance and partial appeal. Experimental searches for predicted unique features of those models are therefore essential to steer theory towards a better and deeper understanding of fundamental laws in nature.

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,

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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 [3].

In this article we can only address a few aspects of a rich spectrum of possibilities.

2 Fundamental fermion properties

2.1 Neutrinos

The SM knows three charged leptons (e^-, μ^-, τ^-) and three electrically neutral neutrinos (ν_e, ν_μ, ν_τ) as well as their respective antiparticles. The members of the lepton families do not participate in strong interactions. Neutrinos eigenstates of mass (ν_1, ν_2, ν_3) and flavor are different and connected to each other 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 ν masses. Among the recent discoveries are the surprisingly large mixing angles Θ_{12} and Θ_{23}. The mixing angle Θ_{13}, the phases for CP violation, the question whether ν's are Dirac or Majorana particles and a direct measurement of a neutrino mass rank among the top issues in neutrino physics [4].

2.1.1 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.

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 Europe [5]. 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 narrowband radio detection will be employed.

The second concept allows directional sensitivity for low energy anti-neutrinos. The reaction $\overline{\nu} + p \rightarrow e^+ + \mathrm{n}$ 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 α-particle from the $\mathrm{n} + \mathrm{B}$ nuclear reaction can be used to determine on average the direction of incoming anti-neutrinos. Such a detector, if scaled to sufficient mass, can be used to determine the distribution of radionuclides in the interior of the earth (including testing the rather exotic of a nuclear reactor in center of the earth) [6].

A further rather promising application of such a detector would be a measurement of the neutrino generation mixing angle Θ_{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 ν's is an indispensable requirement.

2.1.2 Neutrino masses

The best neutrino mass limits have been extracted from measurements of the tritium β-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. This by far overwhelms the possible 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 $m(\nu_e) < 2.2\,\mathrm{eV}$ [7,8].

A new experiment, KATRIN [9], is presently prepared in Karlsruhe, Germany, which is planned to exploit the same technique. 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 new 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 β-decay in ^{76}Ge [10]. The Heidelberg-Moskow collaboration performing this experiment in the Grand Sasso laboratory reports a 4.2 standard deviation effect for the existence of this decay[1]. It should be noted that neutrinoless double β-decay is only possible for Majorana neutrinos. A confirmed signal would solve one of the most urgent questions in particle physics.

Additional work is needed to obtain more accurate values of the nuclear matrix elements which determine the lifetimes of the possible neutrinoless double β-decay candidates. Only then a positive signal could be converted in a Majorana neutrino mass with small uncertainties [11].

2.2 Quarks —unitarity of Cabbibo-Kobayashi-Maskawa matrix

The mass and weak eigenstates of the six quarks $(\mathrm{u}, \mathrm{d}, \mathrm{s}, \mathrm{c}, \mathrm{b}, \mathrm{t})$ are different and related to each other by a 3×3 unitary matrix, the Cabbibo-Kobayashi-Maskawa (CKM) matrix. 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

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[1] A number of further experiments is under way using different candidate nuclei to verify this claim. An extensive coverage of this subject is well beyond the scope of this article.

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

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

where the SM predicts Δ 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 ft values of superallowed β-decays. Other possibilities are the neutron decay and the pion β-decay, which both are presently studied.

V_{us} can be extracted from K decays and in principle also from hyperon decays. One of the triumphs of nuclear physics in contributing to a confirmation of the standard theory had remained covered for a long time by a remarkable misjudgment on the side of the Particle Data Group [12]. This expert panel had decided to increase the uncertainty of V_{ud} from nuclear β-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 persistently reported without true basis [14]. Recent careful analysis of the subject has also revealed overlooked inconsistencies in the overall picture [15,16] and at this time new determinations of V_{us} together with V_{ud} from nuclear β-decay confirm $\Delta = 0$ and the unitarity of the CKM matrix up to presently possible accuracy.

Because of the cleanest and therefore most accurate theory pion β-decay offers for future higher precision measurements the best opportunities, in principle. The estimate [17] for accuracy improvement from nuclear β-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 β-decay.

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 $\sin^2\Theta_W$ appears not to be in agreement with observations [18,19,2]. If the value of $\sin^2\Theta_W$ is fixed at the Z^0-pole, deep inelastic neutrino 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 [20] at the Jefferson Laboratory in the USA. For atomic parity violation [21] in principle higher experimental accuracy will be possible from experiments using Fr isotopes [22,23] or single Ba or Ra ions in radiofrequency traps [24]. 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 [25] 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 β-decays offer excellent opportunities to find new sources of CP violation.

3.2.1 Permanent Electric Dipole Moments (EDMs)

An EDM 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. EDMs 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 [26]. EDMs have been searched for in various systems with different sensitivities (table 1). In composed systems such as molecules or atoms fundamental particle dipole moments of constituents may be significantly enhanced [27,28]. Particularly in polarizable systems there can exist large internal fields.

There is no preferred system to search for an EDM [29]. In fact, many systems need to be examined, because depending on the underlying process different systems have

Table 1. Actual limits on permanent electric dipole moments.

Particle	Limit/Measurement [e-cm]	Reference
e	$< 1.6 \times 10^{-27}$	[30]
μ	$< 2.8 \times 10^{-19}$	[31]
τ	$(-2.2 < d_\tau < 4.5) \times 10^{-17}$	[32]
n	$< 6.3 \times 10^{-26}$	[33]
p	$(-3.7 \pm 6.3) \times 10^{-23}$	[34]
Λ	$(-3.0 \pm 7.4) \times 10^{-17}$	[35]
$\nu_{e,\mu}$	$< 2 \times 10^{-21}$	[36]
ν_τ	$< 5.2 \times 10^{-17}$	[37]
Hg-atom	$< 2.1 \times 10^{-28}$	[38]

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.

This highly active field of research benefited recently from 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. Because they are of opposite parity, a significant enhancement has been predicted for an electron EDM [39], much higher than for any other atomic system. Further more, 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 [40]. From a technical point of view the Ra atomic levels of interest for en 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 [41].

A very novel idea was introduced recently for measuring an EDM of charged particles [42]. The high motional electric field is exploited, which charged particles at relativistic speeds experience in a magnetic storage ring. In such an experiment the Schiff theorem can be circumvented (which had excluded charged particles from experiments due to the Lorentz force acceleration) because of the non-trivial geometry of the problem [27]. 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_{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. 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 [43,42]. 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 some certain new physics models than the present limit on the electron EDM [44]. 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 [45].

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 [46]. It was shown very recently [47] that the deuteron can be in certain scenarios significantly more sensitive than the neutron. In eq. (2) this situation is evident for the case of quark chromo-EDMs:

$$d_{\mathcal{D}} = -4.67\, d_d^c + 5.22\, d_u^c\,, \qquad d_n = -0.01\, d_d^c + 0.49\, d_u^c\,. \tag{2}$$

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 [48]. 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 (BNL), the Indiana University Cyclotron Facility (IUCF) and the Kernfysisch Versneller Instituut (KVI) are considered.

3.2.2 Correlations in β-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 [49]. 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 $\mathrm{d}^2W/\mathrm{d}\Omega_e\,\mathrm{d}\Omega_\nu$ for a β-radioactive nucleus is related to the electron and neutrino momenta $\boldsymbol{p}$ and $\boldsymbol{q}$ through

$$\begin{aligned}\frac{\mathrm{d}^2W}{\mathrm{d}\Omega_e\,\mathrm{d}\Omega_\nu} &\sim 1 + a\,\frac{\boldsymbol{p}\cdot\boldsymbol{q}}{E} + b\,\sqrt{1-(Z\alpha)^2}\,\frac{m_e}{E}\\ &+\langle\boldsymbol{J}\rangle\cdot\left[A\,\frac{\boldsymbol{p}}{E} + B\,\boldsymbol{q} + D\,\frac{\boldsymbol{p}\times\boldsymbol{q}}{E}\right]\\ &+\langle\boldsymbol{\sigma}\rangle\cdot\left[G\,\frac{\boldsymbol{p}}{E} + Q\,\boldsymbol{J} + R\,\langle\boldsymbol{J}\rangle\times\frac{\boldsymbol{q}}{E}\right],\end{aligned} \tag{3}$$

where m_e is the β-particle mass, E its energy, $\boldsymbol{\sigma}$ its spin, and $\boldsymbol{J}$ 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 β-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 [49].

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 atom traps formed by laser light, where many atomic species can be stored at temperatures below 1 mK. An overview over actual activities can be found in [50].

Such research is being performed at a number of laboratories worldwide. At KVI a new facility is being set up, in which T violation research will be a central scientific issue [41,51]. At this new facility the isotopes of primary interest are ^{20}Na, ^{21}Na, ^{18}Ne and ^{19}Ne. These atoms have suitable spectral lines for optical trapping and the nuclear properties allow to observe rather clean transitions.

A recent measurement at Berkeley, USA, the asymmetry parameter a in the β-decay of ^{21}Na has been measured in optically trapped atoms [52]. 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 β-decay, this depends strongly on the $\beta/(\beta+\gamma)$ decay branching ratio for which some 5 measurements exists which in part disagree significantly [53]. New measurements are needed. The most stringent limit on scalar interactions for β-neutrino correlation measurements comes from an experiment on the pure Fermi decay of ^{38m}K at TRIUMF, where a was extracted to 0.5% accuracy and in good agreement with standard theory [54].

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 α or the Rydberg constant R_∞. 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

The interpretation of measurements in the muonium [55] atom, the bound state of a μ^+ and an e^-, is free of difficulties arising from the structure of its constituents [56]. 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 α as well as of muon properties (muon mass m_μ and muon magnetic moment μ_μ). 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_μ, the relative deviation of the muon g-factor from the Dirac value 2. Muonium spectroscopy provides precise values for mass, electric charge and magnetic moment of the muon.

4.1.2 Muon magnetic anomaly

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 at BNL [57]. The quantity a_μ 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 hardrons. Up to now the relevant cross section was determined in the essential energy region in the CMD experiment in Novosibirsk, Russia, or extracted from hadronic τ-decays measured in several setups. Calculations of the hadronic part in a_μ depend on the choice of presently available experimental hadronic data and are obtained from an integration over all energies. The results for a_μ 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. Evaluations of the hadronic corrections based on available new data on e^+-e^- annihilation from the KLOE experiment in Frascati, Italy, appear to confirm earlier values [58], although in small energy intervals significant differences exist in the cross sections from the different experiments. 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 [59] has been seen. A continuation of the g-2 experiment with improved equipment and beams was scientifically approved in 2004.

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 [3]. In [56] two possible scenarios for a 1 GeV and a 30 GeV machine are compared with respect to the physics prospects and the needs of in part novel experimental approaches (see, *e.g.*, [60]). Only a few, but important experiments (like muon g-2) would definitely require the high energy beams. The availability of such a new facility would be desirable for a number of other fields as well, such as neutron scattering, in particular ultra-cold neutron research [61], 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 [60,62], 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.

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