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Fundamental interactions

Some actual developments at low energies

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Abstract Trapped and stored charged particles, atoms and molecules offer a number of opportunities to measure exact values of important fundamental constants such as lepton magnetic anomalies, the fine structure constant and the electron mass. New Physics can be searched for by comparing precise measurements and highly accurate calculations of particle properties. Some recent experiments differ by a few standard deviations from standard theory predictions, such as the muon magnetic anomaly and ^{21}Na β-decay; for a clarification further work is needed.

Keywords Fundamental interactions · Fundamental symmetries · Precision measurements · Magnetic anomalies · β-decays · Electric dipole moments · Radioactive beam facilities

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1 Introduction

The Standard Model (SM) in particle physics describes accurately all observations in particle physics. It appears that even recent spectacular observations in neutrino experiments can be included with moderate modifications. This far ranging theory lacks, however, a deeper and more satisfactory explanation for many described facts. The open questions include the large number of free parameters in the SM, the hierarchy of fundamental fermion masses, the number of three particle generations and the origin of parity (P) violation and combined charge symmetry (C) and parity

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(CP) violation. If combined with Standard Cosmology the dominance of mater over antimatter in the universe remains a mystery. In order to provide answers to such intriguing questions speculative extensions were invented, such as supersymmetry, left-right symmetry, technicolor and many others. However, they have no status in physics, yet, unless they can be experimentally verified.

Two different approaches exist to confirm the SM and to find New Physics beyond it: (1) the direct observation of new particles or processes and (2) precise measurements of quantities, which can be calculated to sufficient accuracy within the SM, and where New Physics appears in a significant difference between theory and experiment. Whereas the first approach usually is carried out in high energy physics, the second approach typically has experiments at low energies. Precision measurements at low energies offer various possibilities to confirm the SM at a high level, to find new physics and to determine accurate values of important fundamental constants [1–3]. Possibilities for stringent tests of the SM arise from a large number of experiments using stored and trapped particles, atoms and molecules. This includes, e.g., precise measurements of magnetic anomalies, precision studies of nuclear β-decays and searches for permanent electric dipole moments.

In recent years, several experiments have reported differences of a few standard deviations between theoretical predictions and the measurements. Among those are experiments on the muon magnetic anomaly, the unitarity of the Cabbibo–Kobayashi–Maskawa matrix, nuclear β-decay, atomic parity violation and many others. In some cases the differences disappeared after refinement of theory, however, not for all of them. Further work is needed to clarify the situation.[1]

2 Known interactions and searches for new physics

Among the known fundamental interactions (gravity, strong, electromagnetic and weak) the electromagnetic interaction is described by the best quantum field theory we have, Quantum Electrodynamics (QED), to very high accuracy. In the development of modern physics the discovery of the magnetic anomaly of electrons $a_e = (g_e - 2)/2$, i.e. the relative deviation of the magnetic g-factor from the Dirac value 2, has played a central role. Its explanation through the ”structure” of the electron acquired from virtual photon, electron and positron fields was an important starting point for the succesful theory of QED. Today the QED part of the lepton magnetic anomalies can be completely calculated to $(\frac{\alpha}{\pi})^3$ analytically and all terms of order $(\frac{\alpha}{\pi})^4$ numerically as well as the major terms to $(\frac{\alpha}{\pi})^5$ [6].

2.1 Electron magnetic anomaly

The electron magnetic anomaly has been determined with single electrons in a Penning trap by measuring the spin precession and cyclotron frequencies (ω_s and ω_c) using the lowest quantized states of motion $a_e = (\omega_s - \omega_c)/\omega_c$. The experiment has

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[1] We concentrate here on some recent developments, leaving important issues such as e.g. the very successful work with antiprotons [4], the high activities around neutrinoless double β-decay [1, 2, 4] and the question of unitarity of the Cabbibo–Kobayashi–Maskawa matrix [5]. These important activities involving trapped particles will be covered by other authors in this volume.

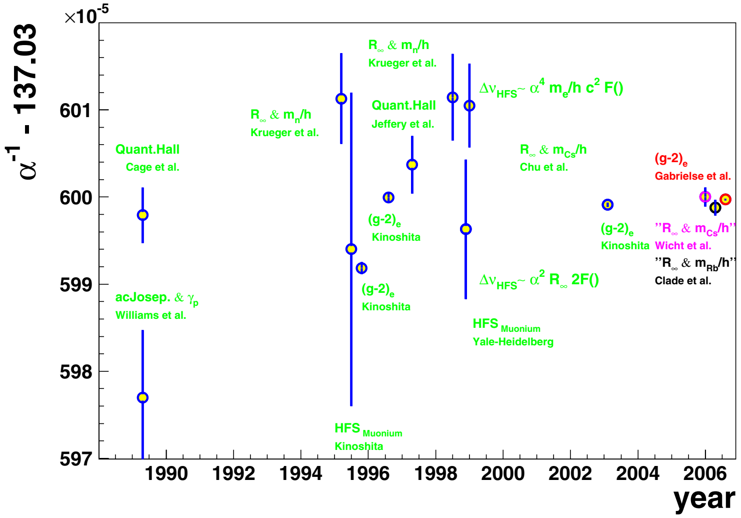

Fig. 1 The fine structure constant α has been measured with various methods, where the most recently determined value for the electron magnetic anomaly [8] yields by far the best value with, on this full scale, uncertainty too small to display. The good agreement between the various values may be interpreted as a stringent test of the internal consistency of QED, as significantly different theoretical approaches are necessary in the various cases

numerous experimental improvements over the famous experiment of Dehmelt et al. in 1987 [7]. In particular, cavity shifts limiting earlier measurements in a hyperbolical trap were eliminated by appropriate operation points in a device with cylindrical symmetry. The outstanding new experiment has yielded $g_e/2 = 1.001\,159\,652\,180\,85(76)$ which has an accuracy of 0.76 ppt and constitutes a factor of 6.5 over the previous experiment. Relying on the correctness of the QED calculations the measured value of a_e can be converted into the most accurate value of the fine structure constant (see Fig. 1) of $\alpha^{-1} = 137.0035\,999\,710(96)$ [8], which is an accuracy of 0.7 ppb.

2.2 Muon magnetic anomaly

The muon is by a factor $(m_\mu/m_e)^2 \approx 40,000$ more sensitive to heavier particles and fields appearing in vacuum polarization loops. This makes it still more sensitive to possible New Physics effects, despite the lower achieved experimental accuracy as compared to the electron case. This was the main motivation for the completed experiment E812 at the Brookhaven National Laboratory, USA, where a_μ was measured for both signs of charge to 0.7 ppm. At present there appears to be a difference of 3.3 standard deviations (see Fig. 2) between the most recently compiled SM value and the published final experimental value [9]. Unfortunately there are still unanswered questions concerning the consistency and full independence of different experiments determining the leading order hadronic corrections to a_μ using electron-positron annihilations into hadrons (+ photons). The incompatibility of the hadronic corrections determined from hadronic τ-decays and electron-positron

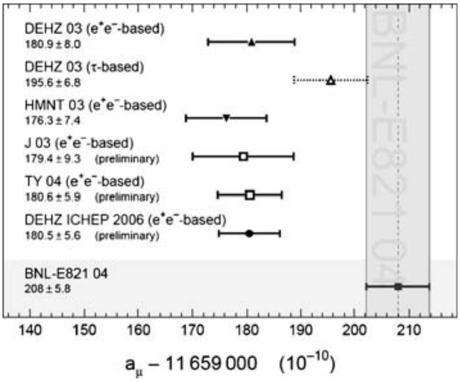

Fig. 2 The latest SM value for the muon magnetic anomaly differs by 3.3σ from the final result of experiment E821 at BNL which is the averaged value for both signs of charge for the muon. Hadronic corrections determined using also hadronic τ-decays were not included in the latest given SM value [10]

Table 1 Values for the electron mass determined in bound state g factor measurements of hydrogen-like ions and in a Penning trap [13, 14]

Method	Electron mass [u]	Experiment
$^{12}C^{5+}$	0.000 548 579 909 32(29)	Mainz/GSI
$^{16}O^{7+}$	0.000 548 579 909 60(41)	Mainz/GSI
Penning Trap	0.000 548 579 911 1(1 2)	Seattle

annihilation presents a puzzle which may relate to the validity of the conserved vector current hypothesis, which is centrally assumed when using τ-data and for which no independent test of sufficient accuracy exists.

2.3 Bound state g-factors

Recently single ion experiments in Penning traps have attracted attention, in which the magnetic g-factor of hydrogen-like bound states was determined. The technology – similar to the single electron experiments – uses a double trap arrangement. Spin flips are induced in a highly homogeneous magnetic field of one of the Penning traps. For a measurement the ions are transferred into a trap with inhomogeneous field which allows the coupling of ion motions in the trap. The hydrogen-like bound state of ions has a g-factor the calculation of which includes beyond the QED calculations arising from virtual electron and photon fields like in the free particle also a dependence on the electron/ion mass ratio (m_e/M_{ion}). This allows to extract the electron mass with higher accuracy than previously determined in a more direct measurement of electrons in a Penning trap (see Table 1) [11, 12]. It can be expected that the experiments will reach a precision that will allow to extract a very precise value for the fine structure constant α, in particular for singly charged ions around carbon where the sensitivity is highest [15]. For heavy ions tests of QED calculations are in the foreground, where beyond finite nuclear size and weak interaction corrections in particular the QED expansion parameter ($Z\alpha$) has a large value and the convergence of perturbation series is slow.

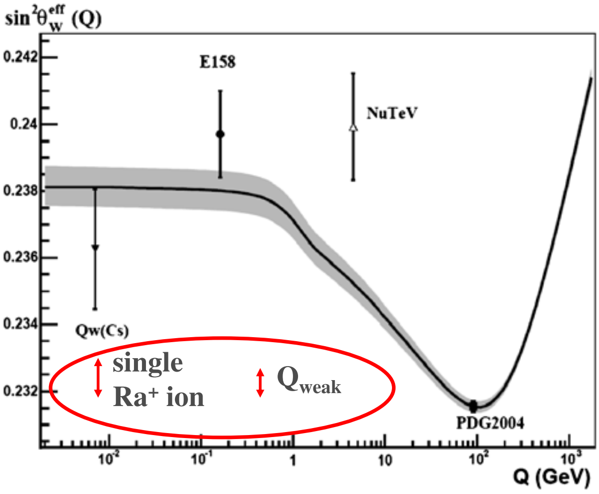

Fig. 3 Running of the weak mixing angle (see [17]). The present test of SM theory is not fully satisfactory. The estimated accuracy of future experiments is indicated in the *inserted* ellipse

3 Discrete symmetries

3.1 Parity

The observation of atomic parity violation was crucial for the acceptance of the SM as a unified electro-weak theory with a validity over several orders of magnitude in momentum transfer. The most recent completed experiment [16] allows to extract a precise value of the weak mixing angle ($\sin^2\Theta_W$). The running with energy (see [17]) of this quantity is such that there is a minimum at the Z-pole and it is higher at lower and at higher energies due to the Abelian respectively non-Abelian character of QED and QCD. The experimental verification of that running is rather moderate (see Fig. 3). Therefore new precision experiments are indicated. Whereas the deep inelastic scattering experiment Q_{weak} at the Jefferson Laboratory (USA) will cover the intermediate energy range a new possibility has emerged at atomic energies. It has been suggested to employ single heavy alkali-like ions and to observe lightshifts in S–D transitions. At the University of Washington promising preparatory experiments using Ba^+ have been performed [18]. Ra^+ ions have not only some 20 times bigger parity effects. The relevant transitions also are easier accessible with all-solid-state laser systems. As parity effects will be extracted in electromagnetic-weak interference, better knowledge of atomic wavefunctions at the sub-percent level will be mandatory – a posed challenge for atomic theorists.

3.2 CP and T-violation

3.2.1 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 [19]. 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 β-radioactive nucleus is related to the electron and neutrino momenta p and q through

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

where m_e is the β-particle mass, E its energy, σ its spin, and 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 has a high sensitivity only within a smaller set of speculative models, since in this area of research there exist some already well established constraints, e.g., from searches for permanent electric dipole moments [19].

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 extremely 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 [20].

Such research is being performed at a number of laboratories worldwide. In a recent measurement at Berkeley, USA, the asymmetry parameter a in the β-decay of ^{21}Na has been measured in optically trapped atoms [21]. The value differs from the present SM value by about three standard deviations. In order to explore whether this could be an indication of new physics reflected in new interactions in β-decay, the $\beta/(\beta+\gamma)$ decay branching ratio was remeasured at Texas A&M and at KVI, because some five measurements existed which in part disagreed significantly. The new values of 4.74(4)% [22] and 4.85(12) % (Achouri, Private communication, 2006) agree well and do not affect the SM prediction in a significant way. The still remaining difference may be explained by Na dimer formation in the trap (Scielzo, Comment during this conference, 2006). 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 is in good agreement with standard theory [23].

3.2.2 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 four 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

Table 2 Actual limits on permanent electric dipole moments [27–30]

Particle	Limit/measurement [e-cm]	Method
e	$< 1.6 \times 10^{-27}$	Tl atomic beam (Berkeley)
μ	$< 2.8 \times 10^{-19}$	muon g-2 storage ring (Brookhaven)
n	$< 3.0 \times 10^{-26}$	stored cold neutrons (Grenoble)
Hg-atom	$< 2.1 \times 10^{-28}$	Hg vapour cell (Seattle)

of permanent electric dipole moments has ruled out more speculative models than any other experimental approach in all of particle physics. EDMs have been searched for in various systems with different sensitivities (Table 2). In composed systems such as molecules or atoms, fundamental particle dipole moments of constituents may be significantly enhanced [24]. Particularly in polarizable systems there can exist large internal fields.

There is no preferred system to search for an EDM [25, 26]. 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. Figure 4 shows how a fundamental EDM may translate into an observable quantity. 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 larger than such expected for elementary particles originating within the popular, usually considered non-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 [31, 32], 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 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.

A very novel idea was introduced recently for measuring an EDM of charged particles. 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 [24]. 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. $a_{\text{eff}} << 1$. 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

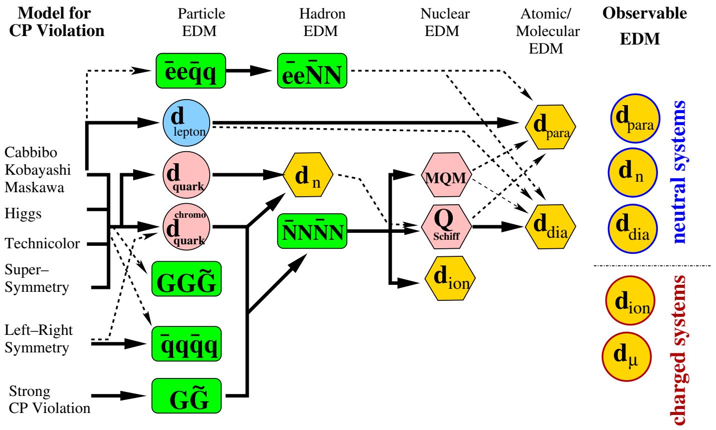

Fig. 4 A variety of theoretical speculative models exists in which an EDM could be induced through different mechanisms or a combination of them into fundamental particles and composed systems for which an EDM would be experimentally accessible. Up to now very sensitive experiments were only carried out for composed neutral systems. A novel technique may allow to sensitively access EDMs also for charged fundamental particles and ions

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 [33]. 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 . 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 [36] that the deuteron can be in certain scenarios significantly more sensitive than the neutron. In equation (3.2.2) this situation is evident for the case of quark chromo-EDMs: $d_{\mathcal{D}} = -4.67\, d_d^c + 5.22\, d_u^c$, $d_n = -0.01\, d_d^c + 0.49\, d_u^c$. 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 beyond 10^{-27} e cm exists. In this case scattering off a target will be used to observe a spin precession [34]. One can expect to extend the method to systems with arbitrary magnetic anomaly, if a relevant parameter on which the signal depends is modulated with the spin anomaly frequency and phase sensitive detection. Modulation of velocity is one option [35].

The highly active field of EDM searches includes at present a variety of experiments on the neutron and the electron EDM. Whereas in the neutron case basically the experiments follow the concepts of earlier measurements, novel approaches characterize the search for an electron EDM. There are continued searches in Hg and a new search in liquid Xe. Further, there are projects on molecules such as PbO, or molecular ions such as ThF^+ or condensed matter such as garnets, where in all cases one relies on the huge predicted enhancements due to local fields [1, 2].

4 Facilities

At present experiments on fundamental interactions and symmetries with trapped particles are either performed in table top laboratory experiments with stable particles in several university laboratories worldwide or at a small number of accelerator laboratories where slow neutrons and radioactive beams are made available. In the latter case the availability of sufficient beam time to debug precision experiments and to study systematic effects with the indicated care is a constant problem. Therefore new facilities are most welcome. The latest commissioned facility is the TRIμP facility at KVI, Netherlands, where fundamental interaction research is foreseen with a significant share of beamtime [37–39]. Among the examples of the there achievable results are studies of the β-decays of $A = 12$ isotopes in excited states of ^{12}C, which may themselves decay into three α particles. Spectra obtained with the radioactive beam ions implanted in a Si detector matrix – another kind of trap – are of relevance to the ^{12}C production process in stars [40].

5 Conclusions

Trapped charged and neutral particles offer a variety of possibilities to investigate fundamental interactions and symmetries and to determine most accurate values of fundamental constants. The present high level of important results can be expected to be even improved in ongoing and planned experiments at existing and next generation facilities, providing information complementary to high energy physics.

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