

Some Aspects of Fundamental Symmetries and Interactions

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Abstract. The known fundamental symmetries and interactions are well described by the Standard Model. Features of this powerful theory, which are described but not deeper explained, are addressed in a variety of speculative models. Experimental tests of the predictions in such approaches can be either through direct observations at the highest possible accelerator energies or through precision measurements in which small deviations from calculated values within the Standard Model are searched for. Antiproton physics renders a number of possibilities to search for new physics.

In modern physics symmetries play an important and central role. Global symmetries are connected with conservation laws and local symmetries give rise to forces [1]. Today four fundamental interactions are known: Electromagnetism, Weak Interactions, Strong Interactions, and Gravitation. They are considered fundamental, because all observed dynamic processes in nature can be traced back to one or a combination of them.

Electromagnetic, Weak and Strong Interactions can be described in one single theory to astounding precision, the Standard Model (SM) [2]. However, the SM leaves yet several intriguing questions unanswered. Among those are, e.g., the number of fundamental particle generations, the hierarchy of the fundamental fermion masses, and 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), although the experimental findings can be well described. Further, the large number of some 27 free parameters in the SM [2] is unsatisfactory.

In order to explain some of the not well understood features in the SM, searches for yet unknown interactions are very important. Such forces are suggested by a variety of speculative models in which extensions to the present standard theory are introduced. There are models with left-right symmetry, fundamental fermion compositeness, new particles, leptoquarks, supersymmetry, technicolor and many more. It is also a major goal to find a unified quantum field theory which includes all the four known fundamental forces. For this, a satisfactory quantum description of gravity remains yet to be found. In this lively area of actual activity string or membrane theories provide promising approaches.

Without secure experimental verification in the future any of these speculative theories will remain without status in physics, independent of the mathematical elegance and their appeal. Experimental searches for predicted unique features of those models are therefore essential to steer theory towards a better and deeper understanding of the fundamental laws in nature. Two main lines of experimental approach are followed at present: (i) the direct observation of new particles and processes at the highest energies

achievable and (ii) the precise measurement of quantities which can be accurately calculated within the SM and where a discrepancy between theory and experiment would indicate new physics. Both methods deliver complementary information.

In this paper we will discuss some recent developments in the field to frame numerous present and future activities in antiproton (\bar{p}) research [3].

FUNDAMENTAL FERMION PROPERTIES

Neutrinos - Mixing, Masses and their Nature

The reported evidence for neutrino (ν) oscillations [4] strongly indicate finite ν masses [5]. In particular, the neutrino mass eigenstates (ν_1, ν_2, ν_3) are mixed in the observed flavor states (ν_e, ν_μ, ν_τ). Among the recent discoveries are the surprisingly large mixing angles Θ_{12} and Θ_{23} . The mixing angle Θ_{13} , the phases for possible CP-violations, and the question whether ν 's are Dirac or Majorana particles rank among the top issues in neutrino physics. Since the oscillation experiments only yield differences of squared masses, a direct measurement of a ν mass is highly desirable[5]. To address the mixing angle and the CP-violation new neutrino beam experiments are proposed using a neutrino factory or β -beams and large new Cherekov detectors [6]. The new accelerators needed might well be suitable to produce intense beams of antiprotons (\bar{p}).

The best neutrino mass limits have been extracted from measurements of the tritium β -decay spectrum close to its endpoint. Spectrometers based on Magnetic Adiabatic Collimation combined with an Electrostatic filter (MAC-E technique) and found $m(\nu_e) < 2.2$ eV [7]. A new experiment exploiting the same technique, KATRIN [8], is presently prepared in Karlsruhe, Germany. It aims for about one order of magnitude improvement. This yields sensitivity to the mass range where a finite effective neutrino mass value of between 0.1 and 0.9 eV was claimed from a signal in neutrinoless double β -decay in ^{76}Ge [9] with a 4.2σ effect. Neutrinoless double β -decay is only possible for Majorana neutrinos. This decay gives not only the best known key to the question of the neutrino nature, it also is the only approach at present towards finding total lepton number violation. It is addressed in several different experiments.

Quarks - Unitarity of Cabbibo-Kobayashi-Maskawa-Matrix

The mass and weak eigenstates of the u, s and b quarks are different and related to each other by a 3×3 unitary matrix, the Cabbibo-Kobayashi-Maskawa (CKM) matrix [10]. Non-unitarity would be an indication of physics beyond the SM and could be caused by many possibilities, including the existence of more than three quark generations. The best test of unitarity results from the first row of the CKM matrix through $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta$, where the SM predicts Δ to be zero. With the present uncertainties only the elements V_{ud} and V_{us} play a role. V_{ud} can be extracted most accurately from ft values of superallowed β -decays, neutron decay and pion β -decay, which all are presently measured. V_{us} can be extracted from K decays and in principle

also from hyperon decays. Some 2.5σ deviation from unitarity had been persistently reported [10, 11]. Recent analysis of the subject has revealed overlooked inconsistencies in the overall picture [12] and at this time new determinations of V_{us} in several K-decay experiments [13] together with V_{ud} from nuclear β -decay [14] confirm $\Delta = 0$ and the unitarity of the CKM matrix.

DISCRETE SYMMETRIES

Violations of the discrete symmetries P, C and T as well as for CP have been directly observed [10] in weak interactions. The combined CPT symmetry is not known to be violated [15]. Assuming CPT being conserved CP violation implies T-violation.

Parity

The observation of neutral currents together with the measurements of parity non-conservation in atoms were important to establish the validity of the SM. Processes over 10 orders in momentum transfer - from atoms to highest energy scattering - are described by the same electro-weak parameters. This is one of the biggest successes in physics.

At the level of highest precision electro-weak experiments [16] questions arose recently, which ultimately may call for a refinement of theory. The predicted running of the weak mixing angle $\sin^2\Theta_W$ appears not to be in agreement with observations [2, 17]. 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 new round of experiments is being started with the Q_{weak} experiment [18] at the Jefferson Laboratory in the USA. In the same context a reported disagreement of atomic parity violation in Cs [19] has disappeared after a revision of atomic theory. For atomic parity violation [20] in principle higher experimental accuracy will be possible from experiments using Fr isotopes [21, 22] or single Ba or Ra ions in radiofrequency traps [23].

At the CERN LEAR facility \bar{p} x-rays from atoms in which a \bar{p} was captured were utilized to obtain information on the neutron mean square nuclear radii [24]. The achieved accuracy is presently limited by nuclear theory. Neutron distributions are expected to be the limiting factor in the theory for the upcoming round of precision experiments on atomic parity violation, in particular for some Fr and Ra isotopes. At a combined radioactive beam and antiproton facility one can expect experiments to determine the neutron radii with sufficiently high accuracy for the theory of atomic parity violation.

Time Reversal and CP Violation

Searches for new sources of CP-violation are particularly motivated because of a possible relation to the matter-antimatter asymmetry in the universe. Sakharov [25] suggested that the observed dominance of matter could be explained via CP-violation in the early universe at thermal non-equilibrium and baryon number violating processes.

(In a later model of Bertolami et al. [26] only CPT violation and baryon number violation are needed.) CP violation as described in the SM is insufficient to satisfy the needs of this model. Permanent Electric Dipole Moments (EDMs) and certain correlation observables in β -decays offer opportunities to find new sources of CP-violation.

An EDM of any fundamental particle violates both P and T invariance. 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. A number of speculative models foresees EDMs as large as the present experimental limits just allow. EDMs were searched in various systems with different sensitivities (for details see e.g. [27]). In composed systems such as molecules or atoms fundamental particle EDMs of constituents may be significantly enhanced [28]. Particularly in polarizable systems large internal fields can exist and can be exploited.

There is no preferred system to search for an EDM [27]. In fact, many objects 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. An EDM may be found an 'intrinsic property' of an elementary particle as we know them, because the underlying mechanism is not accessible. However, it can also arise from CP-odd forces between the constituents, e.g., between nucleons in nuclei or between nuclei and electrons. Such EDMs could be much larger than those expected for elementary particles originating within the usual popular SM extensions.

There are recent novel developments: (i) For Ra isotopes a unique e^- EDM enhancement was predicted in certain atomic states [29, 30] and in certain nuclei (dynamic) octupole deformation may enhance the effect of a nucleon EDM substantially [31]. (ii) A very novel idea was introduced for searching an EDM of a charged particle. The motional electric field is exploited, which charged particles at relativistic speeds experience in a magnetic storage ring. This method can be applied for muons [32] to obtain information on the second generation of particles without strangeness [33, 34] or deuterons [35] to yield higher sensitivity to quark chromo EDMs than in neutrons [36]. This new method may allow also to search sensitively for a \bar{p} EDM. (iii) Molecules such as PbO became experimentally accessible with a high potential to find an electron EDM [37].

A different approach to T-violation comes from nuclear β -decay. 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 [38]. Other possibilities like scalar, pseudo-scalar and tensor interactions which might be possible would be clear signatures of new physics. The spectrum of present searches includes β -asymmetry measurements and measurements of β - ν correlations (see e.g. [3]), where in particular T-violation could be observed.

It should be noted that \bar{p} physics has made significant contributions towards understanding CP-violation and the direct observation of T-violation, e.g., in the context of the CP-LEAR experimental programme [39].

CPT Invariance Tests and Properties of Known Basic Interactions

The invariance of physical processes under a combined CPT transformation relates to a number of basic physical phenomena, such as Lorentz invariance and the (non-) existence of a preferred frame of reference, the equality of particle and antiparticle properties, spin, the existence of fermions and bosons only and many more [15]. Quite often the results of searches for CPT violation are expressed in small relative numbers, such as, e.g., a limit on a relative deviation of particle properties [10]. Here some freedom in the choice of which quantities are compared is frequently used to obtain some small number. However, an interaction based comparison must be considered more physical. To this extent a theoretical model has been proposed by Kostelecky and co-workers [40]. It allows to compare different experimental approaches in a single theory based on the interaction strength of a possible CPT violating term in the Lagrangian. Such terms are treated perturbatively in systems which otherwise can be described well in standard theory. Therefore these measurements are intimately connected to the accurate determination of particle properties and fundamental constants.

Trapped Charged Particles

Trapping and storing of charged particles in combined magnetic and electric fields has been very successfully applied for obtaining properties of the respective species and for determining fundamental constants. Most accurate results were obtained from single trapped and cooled charged particles. The comparison of electron (e^-) and positron (e^+), positive and negative muon (μ^+, μ^-), and proton (p) and antiproton (\bar{p}) has already reached an impressive level of precision.

The magnetic anomaly of fermions $a = \frac{1}{2} \cdot (g - 2)$ describes the deviation of their magnetic g-factor from the value 2 predicted in the Dirac theory. It could be determined for single electrons and positrons in Penning traps by Dehmelt and his coworkers to 10 ppb [41] by measuring the cyclotron frequency and its difference to the spin precession frequency (g-2 measurement). The good agreement for the magnetic anomaly for electrons and positrons is considered the best CPT test for leptons [10, 40]. Accurate calculations involving almost exclusively the "pure" Quantum Electrodynamics (QED) of electron, positron and photon fields allow the most precise determination of the fine structure constant α [42, 43] by comparing experiment and theory for the electron magnetic anomaly in which α appears as an expansion coefficient. One order of magnitude improvement appears possible [44] with a new experimental approach (also involving single cooled trapped particles) which aims for reducing the effect of cavity QED, the major systematic contribution to the previous experiment [45].

Muons have been stored in a series of measurements at CERN and BNL in magnetic storage rings with weak electrostatic focusing. These devices are conceptually equivalent to Penning traps. The latest g-2 experiment [46] yields values for μ^+ and μ^- which agree at the 0.7 ppm level in accordance with CPT. The muon is by a factor $(\frac{m_\mu}{m_e})^2$ more sensitive to heavy particles compared to the electron. The muon g-2 measurements are sensitive to new physics involving heavy particles at 40,000 times lower experimental

precision than would be needed for e^- . Whether the present muon experimental results are in agreement with standard theory remains an open question, as not sufficiently accurate values for corrections due to known strong interaction effects exist yet.

For the first time in 1986 \bar{p} 's could be trapped in a cylindrical Penning trap after moderation of a \bar{p} beam from LEAR at CERN[47]. Effective moderation of MeV \bar{p} 's and their capture were very important, which has led to detailed studies of the range differences when p 's and \bar{p} 's are slowed down in matter, known as the Barkas effect[48]. Further, electron cooling is essential and could be demonstrated already in the early experiments [49]. In a series of measurements in which the cyclotron frequencies were measured the accuracy of the charge to mass ratio for \bar{p} 's could be improved and compared to the proton value. The best results were achieved when a single H^- ion and a single \bar{p} were measured alternatively in the same trap [50]. At present these experiments are interpreted as a CPT test for p and \bar{p} at the level of 9×10^{-11} . A new experiment has been proposed to measure the magnetic g-factor of the \bar{p} using single particle trapping. Similar to measurements on single electrons and positrons the cyclotron and spin precession frequencies shall be determined. One expects for the comparison of p and \bar{p} g-factors an improvement by a factor of 10^6 [51].

Hydrogen and Antihydrogen

Precision spectroscopy of hydrogen and its isotopes (including the exotic ones like positronium (e^+e^-) and muonium (μ^+e^-) atoms) has confirmed bound state QED at a high level of precision and contributed together with numerous precision experiments to the set of well established fundamental constants [52]; among those are the Rydberg constant as the best measured constant, α and the μ mass and magnetic moment.

The reproducibility of high precision in atomic hydrogen laser spectroscopy allowed to set a limit on the time variation of α from two series of repeated measurements of the 1s-2s energy difference long time where $\frac{\partial\alpha}{\partial t}/\alpha = \frac{\partial}{\partial t}(\ln\alpha) = (-0.9 \pm 2.9) \times 10^{-15}y^{-1}$ could be established [53]. An analysis of these long term experiments reveals that they were operated just at the border at which systematic errors are understood in optical spectroscopy, i.e., at the 10^{-13} level of relative accuracy.

Antihydrogen (\bar{H}) was produced first at CERN in 1995 [54]. The atoms were fast as the production mechanism required e^+e^- pair creation when \bar{p} 's were passing near heavy nuclei. A small fraction of the e^+ form a bound state with the \bar{p} . The experiment was an important step forward showing that a few \bar{H} could be produced. Unfortunately, the speed of the atoms does not allow any meaningful spectroscopy. Later a similar experiment was carried out at FERMILAB [55].

The successful production of slow \bar{H} was first reported by the ATHENA collaboration in 2002 [56] and shortly later also by the ATRAP collaboration [57]. Both experiments use combined Penning traps in which first e^+ and \bar{p} are stored separately and cooled. The atoms form when both species are brought into contact by proper electric potential switching in the combined traps. The detection in ATHENA relies on diffusion of the neutral atoms out of the interaction volume and the registration of π 's which appear when the atoms annihilate on contact with matter walls of the container. In ATRAP

the hydrogen atoms are re-ionized in an electric field and the \bar{p} 's are observed using a capture Penning trap. Most of the atoms are in excited states ($n > 15$) which can be seen from the fact that their physical size is above $0.1 \mu\text{m}$ [58]. For spectroscopy the atoms need to be in states with low n , preferentially the ground state. The production of such states is a major goal of the community for the immediate future. The kinetic energy of the produced $\bar{\text{H}}$ atoms is of order 200 meV corresponding to a velocity of 6×10^4 m/s. This is a factor of 400 above the value where neutral atom traps can hold them. Therefore cooling such atoms or identifying a production mechanism for colder $\bar{\text{H}}$ are a central topic.

For laser cooling of $\bar{\text{H}}$ a continuous laser at the H Lyman- α frequency for $\bar{\text{H}}$ cooling has recently been developed [59]. One hopes to achieve the photo-recoil limit of 1.3 mK. Recently a promising new method was demonstrated to obtain $\bar{\text{H}}$. It uses resonant charge exchange with excited positronium to obtain $\bar{\text{H}}$ atoms with essentially the same velocities as the \bar{p} 's in the trap which can be made rather low by cooling. [58, 60].

A main motivation to perform precision spectroscopy on $\bar{\text{H}}$ is to test CPT invariance. There are two electromagnetic transitions which offer a high quality factor and therefore promise high experimental precision when H and $\bar{\text{H}}$ are compared: the 1s-2s two-photon transition at frequency $\Delta\nu_{1s-2s}$ and the ground state hyperfine splitting $\Delta\nu_{HFS}$, which both have within the SM in addition to the leading order contributions from QED, nuclear structure, weak and strong interactions, $\Delta\nu_{1s-2s} = \frac{3}{4} \times R_\infty + \epsilon_{QED} + \epsilon_{nucl} + \epsilon_{weak} + \epsilon_{strong} + \epsilon_{CPT}$ and $\Delta\nu_{HFS} = \text{const} \times \alpha^2 \times R_\infty + \epsilon_{QED}^* + \epsilon_{nucl}^* + \epsilon_{weak}^* + \epsilon_{strong}^* + \epsilon_{CPT}^*$. It is assumed that only CPT violating contributions exist from interactions beyond the SM. If one assumes that ϵ_{CPT} and ϵ_{CPT}^* are of the same order of magnitude, the relative contribution is larger by order $\alpha^{-2} \approx 2 \times 10^4$ for $\Delta\nu_{HFS}$. Further one can speculate that a new interaction may be of short range (contact interaction), which also favors measurements of $\Delta\nu_{HFS}$. Such an experiment has been recently proposed. It utilizes a cold $\bar{\text{H}}$ atom beam and has sextupole state selection magnets in a Rabi type atomic beam experiment [61]. For both experiments temperature of the atoms and statistics governs the reachable precision, i.e. the atoms should be as cold as possible and one should use as many as possible atoms.

Gravitational Force on $\bar{\text{H}}$

One of the completely open questions in physics concerns the sign of gravitational interaction for antimatter. It can only be answered by experiment. A proposal [62] exists in which the deflection of a horizontal cold beam is measured in the earth's gravitational field. The experiment plans on a number of modern state of the art atomic physics techniques like sympathetic cooling of $\bar{\text{H}}^+$ ions by, e.g., Be^+ ions in an ion trap to achieve the necessary low temperatures of some $20 \mu\text{K}$. After pulsed laser photo-dissociation of the ion into $\bar{\text{H}}$ and a e^+ the neutral atoms can then leave the trap. The atom's ballistic path can be measured.

Antiprotonic Helium

The potential of antiprotonic helium for precision measurements in the field of fundamental interaction research was realized shortly after it had been discovered that \bar{p} 's stopped in liquid or gaseous helium exhibit long lifetimes and do not rapidly annihilate with nucleons in the helium nucleus [63]. This can be explained, if one assumes that the \bar{p} 's are captured in metastable states of high principal quantum number n and high angular momentum l , with $l \approx n$ [64]. The capture happens typically at $n \approx \sqrt{M^*/m_e} \approx 38$, where M^* is the reduced mass of the ($\bar{p}\text{He}$) bound system.

With laser radiation the \bar{p} 's in these atoms can be transferred into states where Auger de-excitation can take place. In the resulting H-like system Stark mixing with s-states results in nuclear \bar{p} absorption and annihilation which is signaled by emitted pions. This way a number of transitions could be induced and measured with continuously increasing accuracy over the past decade. A precision of 6×10^{-8} has been reached for the transition frequencies [65], which has been stimulating for improving three-body QED calculations. It should be noted that with the high principal quantum numbers for the \bar{p} the system shows also molecular type character [66].

Among the spectroscopic successes the laser-microwave double resonance measurements of hyperfine splittings of \bar{p} transitions could be measured [67]. There is agreement with QED theory [68] at the 6×10^{-5} level which can be interpreted as a measurement of the antiprotonic bound state g-factor to this accuracy. Hyperfine structure measurements in antiprotonic helium offer the possibility to measure the magnetic moment of the \bar{p} .

The very good agreement of the QED calculations with the measurements of several transitions can be exploited to extract a limit on the equality of the charge² to mass ratio for proton and \bar{p} . Combined with the results of cyclotron frequency measurements [50] in Penning traps one can conclude that masses and charges of proton and \bar{p} are equal within 6×10^{-8} in full agreement with expectations based on the CPT theorem [69]. The collaboration estimates that a test down to the 10 ppb level should be possible.

PRESENT CONTRIBUTIONS OF ANTIPROTON PHYSICS TO FUNDAMENTAL SYMMETRY AND INTERACTION RESEARCH

The antiproton research programmes have made already a number of important contributions to test fundamental symmetries and to verify precise calculations. With cyclotron frequency measurements of a single trapped \bar{p} and with precision spectroscopy of antiprotonic helium ions stringent CPT tests could be performed on \bar{p} parameters. With precise measurements of \bar{p} in antiprotonic helium atomcules the bound state QED three-body systems could be challenged, which has led to significant advances in theory already. With antiprotonic heavy atoms new input could be provided to obtain neutron radii of nuclei, a method that may become important for the theory of atomic parity violation. The differences in proton/ antiproton interactions with matter could expand on similar work with other particle/ antiparticle systems.

$\bar{\text{H}}$ atoms have been produced by two independent collaborations. Precision spectroscopy of these atoms will depend on the availability of atoms in the ground state, the

successful cooling of the systems to below the 100 μeV range and their confinement in neutral particle traps. Work is in progress towards tests of the CPT invariance using the 1s-2s interval or the ground state hyperfine splitting. A comparison with other exotic atom experiments shows that one must allow for sufficient time to develop the necessary understanding of production mechanisms and one must allow time for improving the techniques. The experiments will benefit in their speed of progress and in their ultimate precision from future slow \bar{p} sources of significantly improved particle fluxes and brightness as compared to today's only operational facility. Future possible D^0 decay experiments (e.g. in the context of PANDA at FAIR) have a potential to discover new sources of CP-violation or violation of charged lepton family number. In particular for tests of antimatter gravity cold \bar{H} atoms have a unique potential for a major discovery.

The ongoing and planned experiments bear a robust discovery potential for new physics, in particular when searching for CPT violation. We can look forward to future precision \bar{p} experiments continuing to deepen insights in fundamental interactions and symmetries, providing important data and parameters within standard theory and providing improved searches for new physics in particular with the availability of better \bar{p} sources at CERN [70, 71] or possibly at the future F(L)AIR facility [51].

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REFERENCES

1. T.D. Lee and C.N. Yang, Phys. Rev. **98**, 1501 (1955)
2. W.J. Marciano, hep-ph/0411179 (2004)
3. K. Jungmann, Nucl.Phys.**A751**, 87, (2005), nucl-ex/0501029 and proceedings of the workshop "Physics with Ultra Slow Antiproton Beams", Riken, Japan (2005)
4. A.B. McDonald, Nucl.Phys.**A751**,53 (2005) and K. Nakamura, Nucl.Phys.**A751**, 67 (2005)
5. for a review see, e.g.:Y. Grossmann, hep-ph/0305245 (2003)
6. A. Blondel et al., "Physics with a Multi-MW Proton Source", CERN-SPSC-2004-024 (2004);
7. V.M. Lobashov et al., Phys. Lett. **B460**, 227 (1999); Ch. Kraus et al. Eur.Phys.J.**40**, 447 (2005)
8. J. Angrik et al., FZ Karlsruhe, FZKA 7090 (2005)
9. H.V. Klapdor-Kleingrothaus, Phys. Lett. **B586**, 198 (2004)
10. S. Eidelmann et al., Phys. Lett. **B 592**, 1 (2004); K. Hagiwara et al., Phys. Rev. **D 66**, 010001 (2002)
11. H. Abele et al., Eur. Phys. J. **C 33**, 1 (2004)
12. A. Czarnecki, W. Marciano and A. Sirlin, Phys.Rev.**D70**, 093006 (2004)and references therein
13. J. Ellis, hep-ph-0409360 (2004)
14. J.C. Hardy, Nucl.Phys. **A752**, 101 (2005); J.C. Hardy and I.S. Towner, nucl-th/0412056 (2004)
15. J. Schwinger, Phys. Rev. **82**, 914 (1951); G. Lueders, Dansk. Mat. Fys. Medd. **28**, 17 (1954),Ann.Phys. **2**, 1 (1957); W. Pauli, in: *Niels Bohr and the Development of Physics*, McGraw-Hill (1955), Nuovo Cimento **6**, 204 (1957)

16. E.W. Hughes, in: "In Memory of Vernon Willard Hughes", E.W. Hughes and F. Iachello (eds.), World Scientific, Singapore, p. 154 (2004)
17. A. Czarnecki and W. Marciano, Int.J.Mod.Phys. **A13**, 2235 (1998) and references therein
18. D. Armstrong et al, proposal E02-020 to Jefferson Lab (2002)
19. S.C. Bennett and C.E. Wieman, Phys.Rev.Lett.**82**, 2484 (1999)
20. "Parity Violation in Atoms and Polarized Electron Scattering", B.F. Bouchiat and M.A. Bouchiat (eds.), World Scientific, Singapore (1999); see also: J. Guena, M. Lintz and M.A. Bouchiat, Mod.Phys.Lett. **A**, in print (2005)
21. S.N. Atutov et al., Hyperfine Interactions **146-147**, 83 (2003)
22. E. Gomez et al., physics/0412073 (2004)
23. N. Fortson, in: loc. cit. [20] p. 244 (1999)
24. A. Trzcińska et al., Nucl. Instr. Meth. **B214**, 157 (2004)
25. A. Sakharov, JETP **5**, 32 (1967); M. Trodden, Rev. Mod. Phys. **71**, 1463 (1999)
26. O. Bertolami et al., Phys.Lett.**B395**,178 (1997)
27. K. Jungmann, physics/0501154 (2005)
28. P.G.H. Sandars, Contemp. Phys. **42**, 97 (2001)
29. V. Dzuba et al., Phys. Rev. A **63**, 062101 (2001)
30. G.P. A. Berg et al. Nucl.Instr.Meas.B 204, 532 (2003), K. Jungmann, Acta Phys.Polon.**33**, 2049 (2002)
31. J. Engel et al.,Phys. Rev. **C 68**, 025501 (2003)
32. F.J.M. Farley et al., Phys. Rev. Lett. **93**, 052001 (2004)
33. W.-F. Chang and J.N. Ng, hep-ex/0307006 (2004)
34. K.S. Babu, B. Dutta and R. Mohapatra, Phys.Rev.Lett. **85** 5064 (2000); B. Dutta and R. Mohapatra, Phys. Rev. **D68** (2003) 113008
35. Y. Semertzidis et al., AIP Conf. Proc. **698**, 200 (2004)
36. C.P Liu and R.G.E. Timmermans, nucl-th/0408060 (2004)
37. D. Kawall et al., AIP Conf.Proc.**698**, 192 (2004)
38. P. Herczeg, Prog. Part. and Nucl. Phys. **46**, 413 (2001)
39. A. Angelopoulos et al., Phys.Rep. **374**, 165 (2003)
40. N. Russell, this conference
41. R. Van Dyck, Jr., in *Quantum Electrodynamics*, T. Kinoshita, ed., p. 322, World Scientific (1990)
42. T. Kinoshita and M. Nio, Phys. Rev. **D70** 113001 (2004)
43. T. Kinoshita (ed.), *Quantum Electrodynamics*, World Scientific (1990)
44. G. Gabrielse, priv. comm. (2005)
45. L.S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986)
46. G.W. Bennett et al., Phys. Rev. Lett. **92**, 161802 (2004)
47. G. Gabrielse et al., Phys. Rev. Lett. **57**, 2504 (1986)
48. G. Gabrielse et al., Phys. Rev. **A 40**, 481 (1989)
49. G. Gabrielse et al., Phys. Rev. Lett.**63**,1360 (1989)
50. G. Gabrielse et al., Phys. Rev. Lett. **82**, 3198 (1999);
51. E. Widmann et al., Letter of Intent to GSI/FAIR (2005) <http://www.oaew.ac.at/smi/flair/LOI/FLAIR-LOI-resub.pdf>
52. Peter J. Mohr, Barry N. Taylor, Rev. Mod. Phys. **77**, 1 (2005)
53. M. Fischer et al., Lecture Notes in Physics **648**, 209 (2004); see also: M. Fischer et al., Phys. Rev. Lett. **92**, 230802-1 (2004)
54. G. Baur et al., Phys. Lett. **B 368**, 251 (1996)
55. G. Blanford et al., Phys. Rev. Lett. **80**, 3037 (1998)
56. M. Amoretti et al., Nature **419**, 456 (2002)
57. G. Gabrielse et al., Phys. Rev. Lett. **89**, 213401 (2002)
58. G. Gabrielse, Adv. At. Mol. Opt. Phys. **50** (2004); see also: P. Oxley et al, Phys. Lett. **B 395**, 60 (2004); M. Amoretti et al., Physics of Plasmas **10**, 3056 (2003); M. Amoretti et al., Phys. Rev. Lett. **91**, 0055001-1 (2003); M. Amoretti et al., Phys. Lett. **B 590**, 133 (2004)
59. K.S.E. Eikema et al, Phys. Rev. Lett. **86**, 5679 (2001)
60. C.H. Storry et al., Phys. Rev. Lett. **93**, 263401(2004)
61. E. Wildman et al., Nucl. Instrum. Meth.**B214**, 89 (2004)
62. J. Walz and T. Hänsch, Gen. Rel. Grav.**36**, 561 (2004)

63. T. Yamazaki et al., *Physics Reports* **366**, 183 (2002)
64. S.N. Nakamura et al., *Phys. Rev. A* **49**, 4457 (1994)
65. M. Hori et al., *Phys. Rev. Lett.* **87**, 093401 (2001)
66. T. Yamazaki, in: *The Hydrogen Atom*, S.G. Karshenboim et al. (eds.), Springer, p. 246 (2001)
67. E. Widmann et al., *Phys. Rev. Lett.* **89**, 243402 (2002)
68. V. Korobov and D. Baklanov, *J. Phys. B: At. Mol. Opt. Phys.* **34**, L519 (2001) and *Phys. Rev. A* **57**, 1662 (1998)
69. M. Hori et al., *Phys. Rev. Lett.* **91**, 123401 (2003)
70. N. Kuroda et al., *Phys. Rev. Lett.* **94**, 023401 (2005)
71. P. Belochitskii et al., Letter of Intent to CERN, SPSC-I-231, 2005-010 (2005)