

# EXPERIMENTS SEARCHING FOR NEW INTERACTIONS IN NUCLEAR $\beta$ -DECAY

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Precision measurements of  $\beta$ -decays in nuclei, muons and neutrons allow to search for non V-A contributions in weak interactions and to set limits on parameters relevant to theoretical models beyond standard theory. Novel experiments are possible in particular at presently operating stable beam facilities and at new radioactive beam facilities such as the ISAC facility at TRIUMF, the upcoming RIKEN cyclotron facility in Japan, the new proposed FRIB (RIA) facility and the newly available facility TRI $\mu$ P at KVI. EURISOL is the most powerful and versatile planned radioactive beam facility.

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## 1. Fundamental Interactions

The Standard Model (SM) of particle physics provides a theoretical framework which allows to describe all observations in particle physics to date. Even those recent observations in neutrino physics which suggest the existence of neutrino oscillations can be accommodated with small modifications. However, contrary to this the great success of the SM there remains a number of most intriguing questions in modern physics to which the SM can not provide further clues about the underlying physical processes, although the facts are can be described often to very high accuracy. Among those puzzling issue are the existence of exactly three generations of fundamental fermions, i.e. quarks and leptons, and the hierarchy of the masses of these fundamental particles. In addition, the electro-weak SM has a rather large number of some 27 free parameters, all extracted from experiments.<sup>1</sup>

In all of modern physics, particularly in the SM, symmetries play an important role. Global symmetries relate to conservation laws and local symmetries give forces. Within the SM 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.

In order to gain deeper insights into the not well understood aspects of fundamental physics, a number of speculative models beyond the present standard theory have been proposed. Those include such which involve Left-Right symmetry, fundamental fermion compositeness, new particles, leptoquarks, supersymmetry, supergravity, technicolor and many more. Interesting candidates for an all encompassing quantum field theory are string or membrane (M) theories which among other features may include supersymmetry in their low energy limit. Independent of their mathematical elegance and partial appeal all of these speculative theories will remain without status in physics unless secure experimental evidence for them being reality can be gained in future. Experimental searches for predicted unique features of those models - such as breaking of discrete symmetries - are therefore essential to steer the development of theory towards a better and deeper understanding of the fundamental laws in nature. Such experiments must be carried out not only at high energy accelerators, but also in complementary approaches at lower energies.

Typically the low energy experiments in this context fall into the realm of atomic physics and of high precision measurements. The advanced methods developed over the past decades in these fields are crucial for the success of this research. Precise measurements of properties of weak interactions through muon, neutron and nuclear  $\beta$ -decays are - next to searches for permanent Electric Dipole Moments (EDMs) of elementary particles, nuclei, atoms and molecules, and searches for rare lepton decays - a central subset of indispensable low energy precision particle physics experiments.<sup>2,3</sup>

## 2. Muons

In the absence of exotic muon decays, the measurement of the muon lifetime  $\tau_\mu$  provides the best way to determine the Fermi coupling constant  $G_F$ :

$$\tau_\mu = \frac{192\pi^3}{G_F^2 m_\mu^5} [1 + \delta] \quad ,$$

where  $m_\mu$  is the muon mass and  $\delta \ll 1$  corrects for sufficiently well understood effects of virtual fields. There are three ongoing efforts to improve over the present knowledge: one at the RIKEN-RAL muon facility,<sup>4</sup> and two at PSI, FAST<sup>5</sup> and MuLan.<sup>6</sup> As the muon mass is known from the pioneering and ground breaking precision measurements in exotic atoms,

i.e. from muonium spectroscopy, directly to 27 ppb,<sup>7</sup> the combination of all muon lifetime measurements until now yields  $\tau_\mu = 2.197019(21)\mu\text{s}$  and  $G_F = 1.166371(6) \times 10^{-5} \text{ GeV}^{-2}$  (5 ppm).<sup>6</sup> Its correctness, i.e. the absence of experimental errors and of other than the SM V-A weak interaction contributions, in particular of rare decays, is amongst other issues important for the interpretation of superallowed nuclear  $\beta$ -decays and neutron decays in terms of the unitarity of the Cabbibbo-Kobayashi-Maskawa matrix.<sup>8</sup>

### 3. Nuclei

#### 3.1. Nuclear $\beta$ -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.<sup>9,10</sup> Other possibilities like scalar, pseudo-scalar and tensor type interactions, which might also 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  $\beta$ -decay probability  $d^2W/d\Omega_e d\Omega_\nu$  is related to the electron and neutrino momenta  $\vec{p}$  and  $\vec{q}$  through

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

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 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 EDM searches.<sup>9</sup>

#### 3.2. $\beta$ -asymmetry

The  $\beta$ -asymmetry A observed first in the decay of  $^{60}\text{Co}$  has confirmed the maximal violation of the parity symmetry in weak interactions. This important quantity has been studied in a number of other systems confirming the

V-A structure of weak interactions, i.e.  $A=-1$ . Recently a  $^{60}\text{Co}$  experiment was performed with traditional spin polarization in 9 and 13 T magnetic fields at the university of Leuven. A preliminary value  $A=-0.953(22)$  was obtained, which presently is rechecked.<sup>11</sup>

### 3.3. $\beta$ -neutrino correlations

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 in extreme shallow potential wells. Such exist in atom traps formed by laser light, where many atoms can be stored at temperatures below 1 mK. At a number of laboratories worldwide  $\beta$ - $\nu$  correlations are studied<sup>10</sup>. Recently at Berkeley the asymmetry parameter  $a$  in the  $\beta$ -decay of  $^{21}\text{Na}$  has been measured in optically trapped atoms.<sup>12</sup> The value differs from the present SM value by about 3 standard deviations. In order to explore whether this might be an indication of new physics, the  $\beta/(\beta + \gamma)$  decay branching ratio was remeasured at Texas A&M and at KVI, because some 5 measurements existed which in part disagreed significantly. The new values of 4.74(4)%<sup>13</sup> and 4.85(12)%<sup>14</sup> and agree well and do not affect significantly the SM prediction. The difference may perhaps be explained by Na dimer formation in the trap.<sup>15</sup> The most stringent limit on scalar interactions comes from  $\beta$ - $\nu$  correlation measurements on the pure Fermi decay of  $^{38m}\text{K}$  at TRIUMF, where  $a$  was extracted to 0.5 % accuracy and in good agreement with standard theory.<sup>16</sup>

New upcoming and promising projects are the WITCH experiment at CERN ISOLDE using ions of  $\beta$ -decaying isotopes stored in a Penning trap<sup>17</sup> and the LPCTrap experiment at GANIL, where  $^6\text{He}$  ions are trapped in a Paul (radiofrequency) trap<sup>18</sup> and where first data were already recorded.

### 3.4. Time Reversal Violation

CP violation as observed first in the neutral Kaon decays can be described with a single phase factor in the Cabbibo-Kobayashi-Maskawa formalism. Because of its possible relation to the observed matter-antimatter asymmetry in the universe, CP violation has attracted a lot of attention. <sup>a</sup> CP

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<sup>a</sup>A. Sakharov<sup>19</sup> 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

violation as described in the SM is however not sufficient to explain the excess of baryons. This provides a strong motivation to search for yet unknown sources CP symmetry violation. It is in particular a major driving force behind the EDM searches going on at present. With the assumption of an unbroken CPT symmetry CP violation is equivalent to T violation.

### 3.5. $\beta$ -neutrino correlations of spin polarized nuclei

The possibilities to find T violation include certain correlation observables in nuclear  $\beta$ -decays. They hence offer excellent opportunities to find new sources of CP violation. In  $\beta$ -neutrino correlations the D coefficient<sup>9</sup> (for spin polarized nuclei) have a high potential to observe new interactions in a region of potential New Physics which is less accessible by EDM searches. However, the R coefficient<sup>9</sup> (observation of  $\beta$ -particle polarization) would explore the same areas as present EDM searches or  $\beta$ -decay asymmetry measurements. Such experiments are underway at a number of laboratories worldwide. It will be a prerequisite and crucial for the success of such measurements that nuclear polarization for trapped atoms can be effectively achieved and measured to about  $10^{-4}$  integral over an experiment.

## 4. Searches for Permanent Electric Dipole Moments

Distinctively different precision experiments to search for an EDM are under way in many different systems. A large number of ideas for significant improvements have been made public. Still, the electron and the neutron get the largest attention of experimental groups, although besides tradition there is little which singles out these systems. Nevertheless, there is a large number of efforts in the USA and in Europe using different approaches which all have unique promising features.

In composed systems, i.e. molecules, atoms or nuclei, fundamental particle dipole moments of constituents can be significantly enhanced.<sup>21</sup> For the electron significant enhancement factors are planned to be exploited such as those associated with the large internal electric fields in polar molecules. Recently the completeness of the Schiff moment operator, which describes such enhancements, has been questioned.<sup>22</sup> This may lead possibly to some modifications of presently well established enhancement factors. There is

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baryon number violating processes. The existence of additional sources of CP-Violation is not a necessary condition to explain the baryon asymmetry. Other viable routes could lead through CPT violation and don't need thermal non-equilibrium.<sup>20</sup>

no preferred system to search for an EDM. In fact, many systems need to be examined, because depending on the underlying processes 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 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 those expected for elementary particles originating within the usually considered models beyond the SM.

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,<sup>23,24</sup> 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. 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.

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.<sup>21</sup> 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.  $a_{eff} \ll 1$ . 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.<sup>25</sup> 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.

The deuteron is the simplest known nucleus. 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<sup>26</sup> that the deuteron can be significantly more sensitive than the neutron. 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.

Table 1. Actual limits on permanent electric dipole moments.<sup>27</sup>

Particle	Limit [e-cm]	method
e	$< 1.6 \times 10^{-27}$	Tl atomic beam (Berkeley)
$\mu$	$< 2.8 \times 10^{-19}$	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)

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  $\text{ThF}^+$  or condensed matter such as garnets, where in all cases one relies on the huge predicted enhancements due to local fields.

## 5. Facilities for providing radioactive isotopes for precision experiments

At present experiments on fundamental interactions and symmetries exploiting nuclear properties 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 radioactive nuclids 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 TRI $\mu$ P facility at KVI was recently commissioned. A significant share of beamtime is allocated fundamental interaction research.<sup>28</sup> An example of the achievable clean secondary beams at TRI $\mu$ P was demon-

strated in an experiment on the  $\beta$ -decays of  $A=12$  isotopes in excited states of  $^{12}\text{C}$ , which may themselves decay into 3  $\alpha$  particles. Spectra obtained with beam ions implanted in a Si detector matrix are of relevance to the  $^{12}\text{C}$  production process in stars.<sup>29</sup>

Future possibilities for precision experiments in a large variety of radioactive atoms may include besides FRIB the ISAC facility at TRIUMF, Canada, provided a new target will be installed, the Spiral II facility of GANIL in Caen, France, the radioactive beams at the new RIKEN cyclotrons in the Tokyo area, Japan, and to a limited extent the FAIR facility of GSI in Darmstadt, Germany. At the latter one can look especially forward to the most intense source of slow antiprotons (FLAIR at FAIR). The most intense and versatile facility will be the planned EURISOL facility. It will be based on a MW proton/deuteron driver, which opens also unique possibilities in muon and neutrino physics.<sup>30,31</sup> For the expected progress in precision measurements it will be of crucial importance that the new facilities can be operated to give a significant share of beam time to this research, because sufficient beam is not only important for collecting statistics; it is even more important to cleanly understand all possible systematic effects.

## 6. Neutrons

Precision measurements in neutron decays offer numerous possibilities to study the very same phenomena discussed above.<sup>32</sup> Although it is beyond the scope of this article to discuss any details, the potential of the offered options needs to be checked in the evaluation procedure before deciding on any particular experiment with nuclei (and vice versa) to assure efficient progress in the field. This holds in particular for D and R coefficient measurements. Just as examples: D coefficient measurements in the TRINE and EMIT experiments at ILL and NIST have not yet achieved the accuracy of experiments in  $^{19}\text{Ne}$ , however, the final state interactions are one order of magnitude better known. The FUNSPIN experiment at PSI challenges the R coefficient measurements in  $^8\text{Li}$ . Last but not least, neutron EDM searches have yielded the most stringent limit on strong CP violation.

## 7. Conclusions

There is a variety of well motivated low energy precision experiments with radioactive nuclei. They have unique and robust discovery potentials. Novel ideas have come up in the recent past to use yet not studied systems and new

experimental approaches. They offer excellent opportunities to complement high energy attempts to find physics beyond the SM. The community is eagerly awaiting FRIB and other complementary facilities worldwide to rapidly proceed with the challenging physics programmes.

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## References

1. W.-M. Yao et al., The Review of Particle Physics, J. of Phys. **G 33**, 1 (2006)
2. T. Akesson et al., Towards the European strategy for particle physics: the Briefing Book, Eur.Phys.J. **C51**, 421(2007)
3. K. Jungmann, Fundamental Symmetries and Interactions, Nucl.Phys. **A751**, 87c (2005) and K. Jungmann, Fundamental symmetries and interactions - Some aspects, Eur.Phys.Jour. **A 25**, 677 (2005);
4. D. Tomono et al., Precise Muon Lifetime Measurement with a Pulsed Beam at the RIKEN-RAL Muon Facility, Nucl. Phys. B, **S149**, 341 (2005)
5. C. Casella, FAST: A precision measurement of the muon lifetime  $\tau_\mu$  and  $G_F$ , Nucl. Phys. **BS150**, 204 (2006)
6. D.B. Chitwood et al., Improved measurement of the positive-muon lifetime and determination of the Fermi constant, Phys. Rev. Lett. **99**, 032001 (2007) and references therein
7. W. Liu et al., High precision measurements of the ground state hyperfine structure interval of muonium and of the muon magnetic moment, Phys. Rev. Lett. **82**, 711 (1999)
8. A. Garcia, Unitarity of the CKM matrix, Hyperf. Int. **172**, 23 (2007); H. Abele et al., Quark mixing, CKM unitarity, Eur.Phys.J. **C33**, 1 (2004)
9. P. Herczeg, Beta decay beyond the standard model, Prog. Part. and Nucl. Phys. **46**, 413 (2001)
10. N. Severijns, M. Beck and O. Naviliat-Cuncic, Tests of the standard electroweak model in beta decay, Rev. Mod. Phys. **78**, 991(2006)
11. N. Severijns, priv. com. (2007); I. Kraev, Search for physics beyond the standard electroweak model with brute-force low temperature nuclear orientation, PhD thesis, KU Leuven, Belgium (2006)
12. N.D. Scielzo et al., Measurement of the  $\beta$ - $\nu$  Correlation using Magneto-optically Trapped  $^{21}\text{Na}$ , Phys.Rev.Lett. **93**, 102501 (2004)
13. V.E. Iacob et al., Branching ratios for the  $\beta$ -decay of  $^{21}\text{Na}$ , Phys.Rev.C **74**,015501,(2006)

14. L. Achouri, priv. com. (2006)
15. N. Scielzo, private communication (2006)
16. A. Gorelov et al., Scalar Interaction Limits from the  $\beta$ - $\nu$  Correlation of Trapped Radioactive Atoms, *Phys.Rev.Lett.* **94**, 142501 (2005)
17. V.Y Kozlov et al, The WITCH experiment: towards weak interactions studies. Status and prospects, *Hyperf. Int.* **172**, 15 (2006)
18. A. Mery et al., Search for tensor couplings in the weak interaction, *Europ. Phys. J. Spec. Top.* **150**, 385 (2007)
19. A. Sakharov, Violation of CP invariance and C asymmetry and baryon asymmetry of universe, *JETP Lett. USSR*, **5**, 24 (1967)
20. O. Bertolami et al., CPT violation and baryogenesis, *Phys. Lett. B* **395**, 178 (1997)
21. P.G.H. Sandars, Electric dipole moments of charged particles, *Contemp.Phys.* **42**, 97 (2001) and references therein
22. C.P. Liu et al., Atomic electric dipole moments: The Schiff theorem and its corrections, *Phys. Rev. C* **76**, 035503 (2007)
23. J.S.M. Ginges and V.V. Flambaum, Violations of fundamental symmetries in atoms and tests of unification theories of elementary particles, *Phys.Rep.* **397**, 63 (2004) and references therein.
24. J. Bieron et al., Lifetime and hyperfine structure of the D-3(2) state of radium, *J.Phys.B* **37**, L305 (2004)
25. F.J.M. Farley et al., New method of measuring electric dipole moments in storage rings, *Phys.Rev.Lett.* **93**, 052001 (2004)
26. C.P. Liu and R.G.E. Timmermans, P- and T-odd two-nucleon interaction and the deuteron electric dipole moment, *Phys.Rev.* **C70**, 055501 (2004)
27. B.C. Regan et al., New limit on the electron electric dipole moment, *Phys.Rev.Lett.* **88**, 071805 (2002); R. McNabb et al., An Improved Limit on the Electric Dipole Moment of the Muon, hep-ex/0407008; C.A. Baker et al., An Improved Experimental Limit on the Electric Dipole Moment of the Neutron, hep-ex/0602020 (2006); M.V. Romalis et al., A New limit on the permanent electric dipole moment of Hg-199, *Phys.Rev.Lett.* **86**,2505( 2001)
28. G.P. Berg et al., Dual magnetic separator for TRI $\mu$ P, *Nucl.Instr.&Meth.* **A560**, 169 (2006); K. Jungmann et al., TRI $\mu$ P - trapped radioactive atoms - microlaboratories for fundamental physics, *Physica Scripta* **T104**, 178 (2003); E. Traykov et al., Production of Radioactive Nuclides in Inverse Reaction Kinematics, *Nucl. Instr. & Meth.* **572**, 580 (2007); H. Wilschut et al., Status of the TRI $\mu$ P project, *Hyperfine Interactions* **174**, 97 (2007)
29. S.G. Pederson et al.,  $\beta$ -decay studies of states in  $^{12}\text{C}$ , *Proc. of Science, NIC-IX*, 244 (2006)
30. P.A. Butler, The first steps to EURISOL, *Act. Phys. Pol.* **B 38**, 1147 (2007)
31. A. Branyopadhyay et al., Physics at a future Neutrino Factory and super-beam facility, arXiv:0710.4947 (2007)
32. J.S. Nico and W.M. Snow, Fundamental Neutron Physics, *Ann. Rev. Nucl. Part. Phys.* **55**, 27 (2005); M. Schumann, Precision Measurements in Neutron Decay, arXiv:0705.3769v1 (2007)