

4. Studies of fundamental interactions

Despite its large phenomenological success, the Standard Model is not generally considered a “fundamental” theory because it uses a large number of parameters that rely on experimentally determined quantities and a number of seemingly arbitrary assumptions. As a consequence, many possible extensions to the present Standard Model have been proposed that predict new exchange particles or extended symmetries.

Tests of the predictions of the Standard Model have to be performed in different energy regimes. High-energy collider and electron-electron scattering experiments are required as are precision decay studies and atomic spectroscopy. These results complement each other and are needed for indicating how the Standard Model may have to be modified. At low energies, precision measurements in nuclear β -decay [Sev06] are a powerful approach to search for violations of the fundamental symmetries and to search for new interactions. Furthermore, precise studies of atomic transitions give access to the study of parity nonconserving lepton-quark interaction. Low-energy rare isotope beams are an important tool for such studies. Progress will come from advances in rare isotope production, e.g., higher yields and better beam quality; the development of new experimental techniques, e.g., atom and ion trapping of rare isotopes; and the possibility of achieving high nuclear polarizations in beams and samples of rare isotopes. Another advance towards expanding the experimental opportunities for fundamental interaction and symmetry studies is the recently demonstrated conversion of beams of fast projectile fragments into high-quality low-energy beams that can be used for precision experiments. An advanced gas-stopping technique being implemented at the NSCL will be used at the ISF, providing intense low-energy rare isotope beams that are difficult or impossible to produce via the ISOL method.

4.1 Test of CVC and determination of V_{ud}

The study of superallowed β decays of nuclei near $N = Z$ has long been used as a powerful tool for probing basic concepts of the Standard Model of Electroweak Interactions [Har05a,Har05b]. One of its key features is the conserved vector current (CVC) hypothesis, which postulates that the vector-current part of the weak interaction is not influenced by the strong interaction. A consequence of CVC is that the strength of superallowed $0^+ \rightarrow 0^+$ β decays, given by the nuclear decay matrix element, should be the same for all nuclei undergoing superallowed β decay, except for a number of small theoretical corrections. The strength of superallowed Fermi-type β decays has been measured with very high precision for isotopes ranging from ^{10}C to ^{74}Rb . The resulting FT-values (Figure 4.1), which include small nuclear and radiative corrections at the percent level, confirm the CVC hypothesis remarkably well at a level of a few 10^{-4} .

From the average FT value, the weak vector coupling constant G_V can be determined. Combining this value of G_V with purely leptonic muon decay data gives us the most precise value of the up-down quark matrix element V_{ud} of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which relates the weak quark eigenstates to the mass quark eigenstates. Using the value for V_{ud} together with V_{us} from kaon decay and V_{ub} from B meson decay allows for a test of the unitarity of the CKM matrix. A nonunitarity of the CKM matrix could have important implications, such

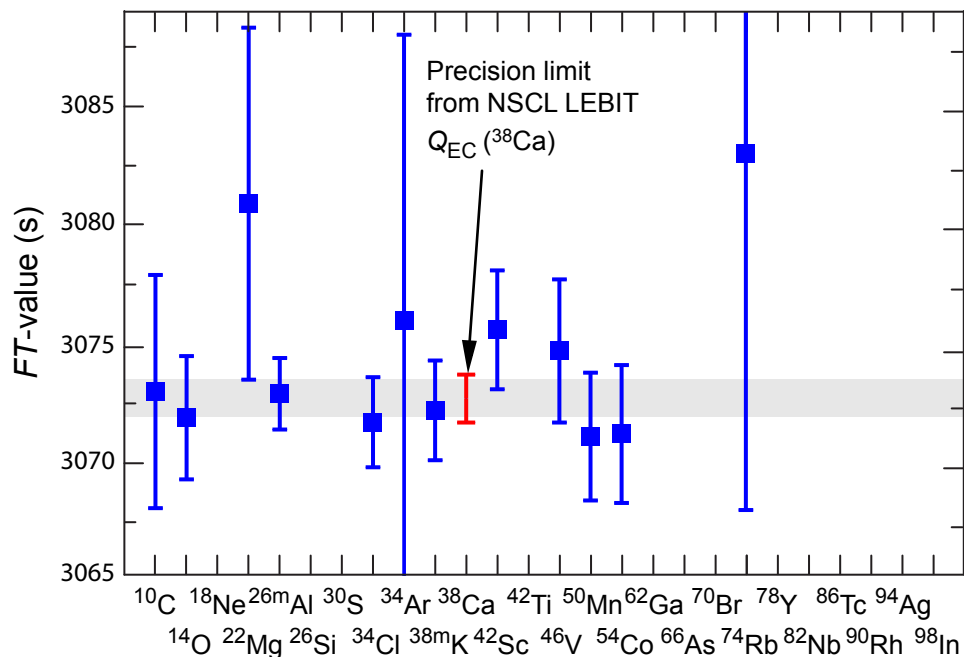


Figure 4.1: FT-values for superallowed β emitters. The horizontal band gives the uncertainty of the average value of 3073.5(12) s. Adapted from [Har05b]. In the case of ^{38}Ca , not all information exists to determine the FT-value. The error bar indicates the precision limit due to the Q_{EC} value alone, which has recently been improved by more than an order of magnitude in a Penning-trap mass measurement with the LEBIT facility at the NSCL [Bol06b].

as the existence of a fourth generation of quarks, exotic fermions, or the need to include right-handed currents in the weak interaction.

For more than 10 years, the unitarity test of the CKM matrix has resulted in a deviation from unitarity by more than two standard deviations. Results from newer kaon decay studies indicate a larger average value for V_{us} than previously assumed that would restore the unitarity of the CKM matrix within the present uncertainties [Yao06]. However, there are still open questions with respect to the calculation of the necessary kaon-to-pion form factor [Ram06]. Furthermore, recent precision mass measurements [Sav05] propose a significant change of the electron capture Q_{EC} value for ^{46}V . It appears prudent to revisit the well-known cases and to improve the precision and accuracy of the experimental data as new and improved techniques become available. It remains important to obtain new experimental data for the determination of precise FT-values of superallowed β emitters. Such data are necessary to extend the set of nuclei for testing CVC beyond the few well-known cases, to benchmark the calculation of the necessary theoretical corrections, and for eventually testing CVC and determining V_{ud} with higher precision.

The required measurements are precise mass differences between mother and daughter nuclei (giving the decay Q -value), decay half-lives, and $0^+ \rightarrow 0^+$ branching ratios. Of particular interest are those decays for which theoretical isospin-symmetry-breaking corrections are large. Assuming CVC, precise data on these candidates provide a sensitive test of the theoretical corrections and will help to improve their calculation. Examples of such candidates are ^{30}S , ^{38}Ca , ^{62}Ga , ^{66}As , and ^{70}Br . Work on these candidates is already going on. A recent example is ^{38}Ca

[Bol06b] in which a mass accuracy of 280 eV has been achieved via a Penning-trap mass measurement with the LEBIT facility at the NSCL. In order to test CVC under more extreme conditions, it is desirable to extend the study of superallowed decays to nuclei heavier than ^{74}Rb . These measurements are challenging because of decreasing production rates, short half-lives, and more complicated decay schemes. High beam rates are required together with high-efficiency detectors for γ rays, β rays, and conversion electrons. A high-performance Penning-trap mass spectrometer is needed for the mass measurements. Furthermore, improvements in the calculation of the theoretical corrections (see for example [Mar06]) will be decisive for utilizing the full impact of the new and improved experimental results.

At the present NSCL facility, it will be possible to determine masses and partial half-lives of most superallowed β emitters up to $A = 70$ with a precision useful for the test of CVC. For the mass measurements, an overall stopping, beam manipulation, and detection efficiency of 10% is assumed, which should be even exceeded once the cyclotron stopper is in place. With the beam rates available at the ISF, it will be possible to extend high precision studies of superallowed β emitters beyond $A = 74$ up to $A = 90$. With beam rates in most cases far above 1000 s^{-1} , the determination of the partial half-lives will be possible with a precision similar to that for the present well-known cases. Relative mass accuracies of better than 10^{-8} will be achievable for all isotopes along the $N = Z$ line with a high-performance Penning-trap mass spectrometer like the one in the LEBIT facility. New ft -values for heavier, superallowed β emitters will provide an excellent testing ground for shell model calculations that predict the required isospin-breaking corrections. Better Hamiltonians for the pf shell are becoming available [Hon02], and the computational ability to include $g_{9/2'}$ required for the heavier candidates, is becoming more feasible.

4.2 Atomic parity violation

The study of atomic parity violation has been pursued over about three decades, but accuracies below the 1% level have only been achieved in recent years. The atomic parity violation [Bou97] is predominantly caused by the direct Z_0 exchange between electrons and a nucleus. This neutral current leads to a mixing of S and P states in the atom, which can be observed in forbidden electric dipole transitions between states of the same parity. Since this mixing scales with Z^3 , the search for atomic parity violation is best performed in heavy atoms. Atomic parity violation studies provide important tests of the Standard Model and a precise determination of its parameters, such as the weak mixing angle θ_w . A small nuclear-spin dependent part of the atomic parity violation arises from the interaction of electrons with the nuclear Schiff moment and the anapole moment. Its observation provides a unique probe of parity violation in purely hadronic nuclear interactions [Hax01]. The anapole moment has been observed in an experiment with stable cesium atoms [Woo97].

A particularly interesting case in which to study atomic parity violation is francium [Gom06]. The size of the weak effects in francium is more than ten times larger than in cesium. Its atomic structure is simple enough to permit necessary atomic structure information to be calculated with the required precision. Furthermore, the choice of different isotopes allows nuclear corrections to be minimized. Eventually, the difference of the weak interactions with protons or with neutrons could be studied.

Pioneering work on francium has been performed at Stony Brook and experiments are planned at ISAC at TRIUMF. The low-energy beam rate required is about 10^6 s^{-1} [Gom06]. At the ISF, fast-beam fragmentation of uranium will provide beam rates for the long-lived isotopes ($T_{1/2} > 100 \text{ s}$) that are high enough for such studies.

4.3 Tests of parity and time reversal symmetries

The CPT theorem requires invariance under the combined application of three independent operations, namely charge conjugation (C), parity inversion (P), and time-reversal (T). Direct evidence for CP violation in the decay of the neutral kaon [Chr64], which is now implemented in the framework of the Standard Model, led immediately to searches for possible T violation. CP violation is thought to have played a crucial role in producing the excess of matter over antimatter early in the history of the universe [Din04]. The Standard Model does not violate the CP symmetry strongly enough to account for this excess. To understand baryogenesis, the physical process of generation of nucleons in the early universe, we must first discover the additional CP violation, if it indeed exists. As a complementary symmetry to the CP symmetry, a test of T invariance is essential to address such an important question.

One such effort is the determination of electric dipole moments (EDM), which violate parity as well as time-reversal invariance. Experiments to detect a nucleon EDM have been performed with ultra-cold neutrons and set a constraint as $|d_n| < 6.3 \times 10^{-26} \text{ ecm}$ (90% CL) [Har99]. On the other hand, the EDM of an atom (or molecule) may result from the EDMs of nucleons, electrons, and/or the P- and T- violating interactions among them. The most stringent constraint was set by the measurement of a diamagnetic ^{199}Hg state as $|d| < 2.1 \times 10^{-28} \text{ ecm}$ (95% CL) [Rom01]. An experiment on a paramagnetic ^{205}Tl state gave an electron EDM limit of $|d_e| < 4 \times 10^{-27} \text{ ecm}$ [Com94]. As shown in Figure 4.2, this is already close to the electron EDM prediction by the super symmetric model, the left-right symmetric model, and the Higgs model.

The sensitivity in observing EDMs can be enhanced by studying heavy rare isotopes. Due to relativistic effects, the measurable electron EDM in atomic systems is proportional to Z^3 [San65]. Therefore measurements on the heavier Z atoms are more sensitive to the EDM. Francium is a very good candidate because of its simple atomic structure. Hadronic EDMs observed in diamagnetic atoms can experience large enhancement factors (100–1000) if the nucleus is octupole-deformed [Fla95a,Spe97]. Such deformations exist in rare isotopes of radon, radium, and francium.

New experiments with higher precision are required in a variety of atomic systems. They will help us to learn to what extent EDMs exist and may contribute to the understanding of the matter-antimatter asymmetry in our universe. Examples of rare isotopes considered for EDM studies are ^{211}Rn , $^{223,225}\text{Ra}$, and ^{221}Fr . Rates for the low-energy beams higher than 10^7 s^{-1} are required for these studies and will be available at the ISF from fast beam fragmentation and gas stopping.

Complementary searches for CP violation can be performed in low energy β -decay experiments. Time-reversal violation tests via correlation experiments in β -decay require an odd number of spin and/or momentum vectors, which is odd in time-reversal operations. The results of the nuclear β -decay experiments on the neutron

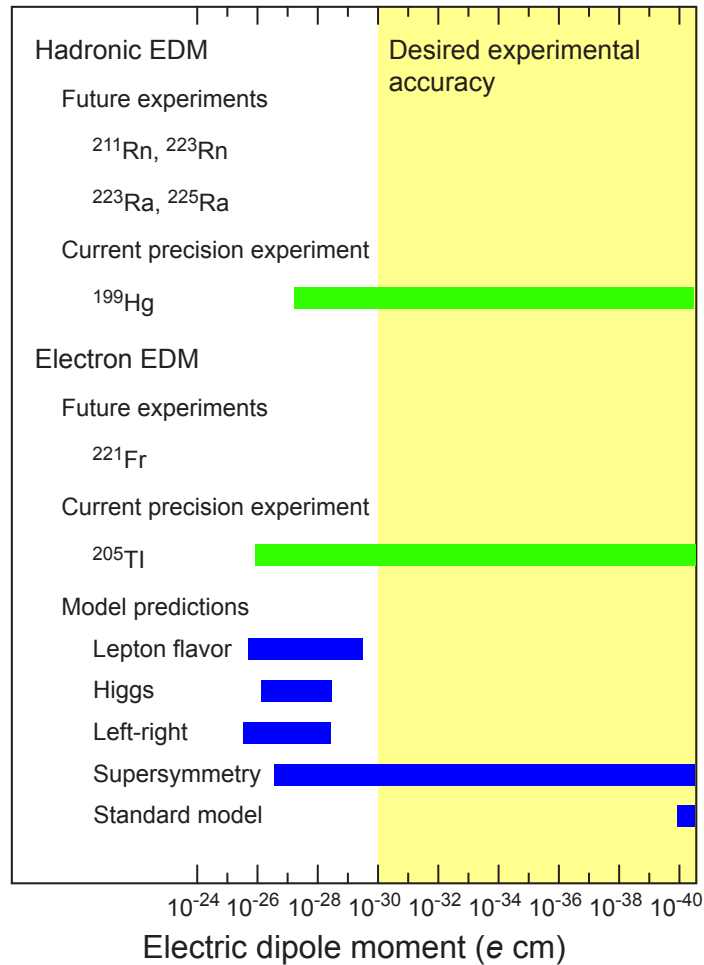


Figure 4.2: Experimental limits for electric dipole moments (EDM) observed in atoms together with rare isotopes that are candidates for future studies. In the case of the electron EDM, theoretical predictions are shown.

[Lis00,Sol04], ⁸Li [Hub03], ¹⁹Ne [Cal74,Bal77,Hal84], and ⁵⁶Co [Cal77] are all consistent with T invariance and the Standard Model. A potentially more precise time-reversal violation test can be obtained in a β-γ-ray angular correlation experiment from spin-aligned nuclei [Mor57,Hol72]. This type of experiment has been performed in the case of ⁵⁶Co; however, it provides the poorest constraint on T-violating coefficients. The superallowed β emitter ³⁶K has been suggested as a very good candidate [You95]. Nuclear alignment can be achieved by laser polarization of a low-energy beam. The required beam intensity to achieve a result that provides a constraint on T-violation better than that from previously studied D and R coefficients is > 10⁷ s⁻¹. Another promising candidate is ⁵²Co. Since optical pumping is difficult, a beam intensity of about 10⁸ s⁻¹ is required to compensate for the smaller nuclear alignment obtained in the beam production reaction. Both experiments will be possible at the ISF.

4.4 Search for new interactions in the weak nucleon current

The Standard Model describes the β-decay process in terms of an exchange of charged vector bosons between the hadronic and leptonic currents. Only vector

and axial-vector type interactions are allowed in the Standard Model. However, scalar and tensor type interactions could exist and, at present, are only ruled out at a level of about 10%. Finding such new interactions would provide a signature of new physics beyond the Standard Model, possibly requiring the exchange of leptoquarks or new charged bosons.

The FT-value confirmation of CVC, discussed above, over wide ranges of Q -values, tests at least one explicit particle physics model of scalar interactions. The Q -dependence of the ft values sets direct stringent limits on scalars that couple to Standard Model neutrinos by constraining the “Fierz” scalar-vector interference term. In certain R -parity violating SUSY models, this observable could be large. The sensitivity for observation is inversely proportional to Q , so the higher Q -values available in heavier $N = Z$ nuclei constrain the baseline value. Greater sensitivity to this observable could test a particular assumption about the SUSY models that is difficult to constrain with collider studies [Ram06].

A promising approach to search for new interactions in the weak nucleon current are β -decay studies, in which the correlation between the directions of emission of the β -particle and the neutrino is studied. This correlation depends on the coupling constants for the various interactions and hence provides the key for the search for exotic currents. Scalar currents can be searched for in pure Fermi decays and tensor currents in pure Gamow-Teller decays.

Since the neutrino cannot be detected directly, the electron-neutrino angular correlation coefficient is determined by studying the correlation between the β particle and the recoiling ion. The direction of the recoiling ion can be either measured directly or can be deduced from the measurements of the Doppler shift of the γ radiation emitted or the kinematic shift observed in the delayed proton or α decay of the recoil nucleus.

These experiments are difficult because small effects have to be observed and sources of systematic errors have to be understood. Therefore, only a few high precision experiments have been performed to date. The most stringent limit on scalar currents comes from a delayed proton-emission experiment on ^{32}Ar at ISOLDE [Ade99] and an atom trap experiment with $^{38\text{m}}\text{K}$ at ISAC [Gor05]. The most precise experiment searching for tensor currents was carried out with ^6He at Oak Ridge more than four decades ago [Joh63]. All these experiments are still in agreement with Standard Model predictions. A recent atom trap experiment [Sci04] with ^{21}Na performed at Berkeley shows a large discrepancy with the Standard Model prediction, though further work confirms systematic trap effects – photo-assisted production of molecular dimers – that are in the process of being controlled.

New electron-neutrino correlation experiments are in preparation and it is interesting to note that they all use either ion or atom traps. The possibility of suspending ion or atom ensembles that are nearly free in space is the key to achieving the highest accuracy. Examples of new developments are WITCH [Koz06b] at ISOLDE, a large magnetic recoil spectrometer connected to a Penning trap, a Paul trap experiment [Rod05] at LPC-Caen for the search for tensor currents in ^6He decay, as well as the TRI μ P facility [Jun03] at KVI-Groningen, where atom traps will be employed for correlation studies similar to those performed at Berkeley and ISAC.

In addition to the nuclei already in use, other interesting candidates for electron-neutrino correlation studies in ion traps are ^{14}O , $^{26\text{m}}\text{Al}$, ^{33}Cl , ^{35}Ar , ^{42}Sc , ^{46}V , ^{50}Mn , and

^{54}Co . The minimum required beam rate depends on the specific experiment. A rate of 10^8 s^{-1} is assumed to be a reasonable lower limit for decay correlation studies using ion traps. With the likely exception of ^{35}Ar , it appears to be difficult or impossible to achieve such beam rates with the ISOL technique, even at a high beam power of 100 kW. At the NSCL, low-energy beam rates close to 10^8 s^{-1} will be available for $^{26\text{m}}\text{Al}$, ^{33}Cl , and ^{35}Ar . At the ISF, the rates exceed 10^8 s^{-1} for all candidates, making this facility a prime place for such studies.

4.5 Search for induced currents in weak interactions

The Standard Model predicts that β decays can be described by the vector – axial vector (VA) form of the weak nucleon current. Even if scalar (S) and tensor (T) interactions in the fundamental weak quark-lepton interactions do not exist, currents can be induced by the strong interaction due to pion exchange in the nucleus (for a review see [Gre85]).

In the vector current, two of the induced terms are the weak magnetism f_W and the induced scalar term f_S . In the framework of the CVC theorem, where the weak currents and the isovector part of electromagnetic current form an isospin triplet, f_W and f_S are exactly given. The scalar term f_S should be zero and, experimentally, has been determined to be small ($f_S < 0.0013$ [Har05b]). Theory predicts a nonzero value for the weak magnetism f_W , which is yet to be determined experimentally with good precision. In the case of the axial vector current, two terms may be induced, a pseudo-scalar term, f_P , and a tensor term, f_T . The f_P term can be determined in muon capture reactions. The f_T term is known as a Second Class Current (SCC) [Wei58,Wil00]. According to the Standard Model, it should be zero. However, the small mass difference between proton and neutron (and hence up and down quarks) may result in a small but finite number, $f_T \sim 10^{-5}/\text{MeV}$ [Shi96]. The most stringent constraint $f_T < 2 \times 10^{-4}/\text{MeV}$, obtained from β -decay angular distribution from aligned ^{12}B and ^{12}N [Min02], does not reach that level.

One possibility for searching for weak magnetism f_W in the vector current interaction is a systematic and very precise measurement of the spectral shape of β -decay energy spectra observed in pure $1 \leftrightarrow 0$ Gamow-Teller transitions, where a simple interpretation of the shape factor is possible. Because the effect of f_W on the spectral shape appears in the form of $\sim f_W E_{\beta^p}$, high-energy β decays are preferred. At the NSCL, a remeasurement of a shape factor of ^{12}B and ^{12}N with higher precision would be possible. At the ISF, the $^{24\text{m}}\text{Na}$ and $^{24\text{m}}\text{Al}$ isospin $T = 1$ pair would be available with required beam rates $> 10^8 \text{ s}^{-1}$, allowing the currently very small set of test cases to be extended. For the determination of the shape of the β -decay energy spectrum with high precision and efficiency, an ion trap based spectrometer similar to the WITCH facility [Koz06b] at ISOLDE, already mentioned above, would be a good choice.

For a precise determination of the induced tensor term f_T in the axial vector current interaction, a measurement of the β decay angular distributions from spin-aligned mirror nuclei can be employed. Taking advantage of the mirror symmetry, the results for both nuclei allow systematic effects to be minimized, which is essential to extract the very small effect of the induced tensor term f_T . Polarized beams are required. Candidates for which polarization can be achieved via laser excitation are preferred because of the much larger degree of polarization achievable compared

to using reactions. A very promising example is ^{13}O . The high β -decay energy and a pure GT transition make ^{13}O very sensitive to f_T . The polarized ^{13}O beam can be obtained by optical pumping, starting from a metastable atomic state [Tin90]. For competitive measurements, low-energy ions with a beam rate of $> 10^7 \text{ s}^{-1}$ are typically required. The necessary measurement of the mirror partner ^{13}B is also possible at the NSCL. It could be performed if a ^{13}B experiment in progress at Osaka University would not succeed. It will be important to study more candidates to put a reliable limit on the induced tensor term. In addition to the $A = 13$ mirror system, the isospin $T = 3/2$ ^9Li - ^9C mirror pair can be studied at the NSCL. At the ISF, the studies could be extended to the $T = 1$ isospin pair $^{24\text{m}}\text{Na}$ - $^{24\text{m}}\text{Al}$, and the $T = 3/2$ pairs ^{21}F - ^{21}Mg and ^{25}Na - ^{25}Si .