Weak Interaction Studies by Precision Experiments in Nuclear Beta Decay

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Abstract. The framework and formalism related to the study of symmetries and the structure of the weak interaction in nuclear β-decay are presented and discussed. This is illustrated with a number of selected experiments in nuclear β-decay addressing the unitarity of the Cabibbo-Kobayashi-Maskawa matrix, the search for right-handed (V+A), scalar and tensor components in the weak interaction and the search for non-Standard Model sources of time reversal violation. Finally, an outlook is given on important progress in this field that can be expected for the near future.

1 Introduction

Nuclear beta decay has contributed significantly to the development of the weak interaction theory. A number of basic foundations of the standard electroweak model, i.e. the assumption of maximal parity violation, the two-component theory (viz. the helicity) of the neutrino and the vector-axial vector character of the weak interaction were discovered in nuclear beta decay processes. The confrontation of the weak interaction theory constructed on the basis of low energy phenomena with the results obtained at higher energies motivated the development of a gauge theory of the weak interaction and constituted a significant step leading to the construction of the unified standard electroweak model.

The formalism for nuclear β-decay has been firmly established and tested already more than three decades ago and was embedded into the larger framework of the standard electroweak model. Since then the main motivations of new experiments performed at low energies with ever higher statistical accuracy have been to provide precision tests of the discrete symmetries, search for non-Standard Model interaction components and to consider specific questions involving the light quarks which are best addressed in nuclear and neutron decays.

In this chapter first the main aspects of the Standard Model relevant to nuclear β-decay will be presented. Thereafter the β-decay interaction hamiltonian will be described from a historical perspective. This will allow to discuss the formalism relevant to the determination of ft-values and correlations between the spin and momentum vectors in nuclear β-decay, which

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are used to test different symmetries of the weak interaction as well as its basic structure. Finally, this is illustrated by a discussion of a number of selected experiments in nuclear β-decay to test the unitarity of the Cabibbo-Kobayashi-Maskawa matrix, to search for a right-handed $V + A$ component or for more exotic scalar or tensor components in the weak interaction and to search for a possible time reversal violating contribution.

Whereas the aim of this contribution is primarily to provide an introduction to the main aspects of the formalism relevant to weak interaction studies in nuclear β-decay and to illustrate this by a number of experiments, the interested reader can find more details and a more advanced discussion of this subject in [1].

Note that several other interesting aspects and applications of nuclear β-decay, mainly related to the study of nuclear structure far from the stability line, are discussed in other lectures in this book [2–5].

2 The Standard Model of Particles and Forces

2.1 Elementary Particles, Intermediate Bosons and Forces

As far as presently known only 12 particles and their corresponding anti-particles are needed to explain all known processes in nature. These truly elementary particles are 6 quarks (the individual quark states being called *flavors*) and 6 leptons:

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix} \text{ and } \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \text{ and } \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

and their corresponding anti-particles. The *up* (u), *charm* (c) and *top* (t) quarks have a charge $q = +2/3$, the *down* (d), *strange* (s) and *bottom* (b) quarks a charge $q = -1/3$. As for the leptons, the *electron* (e), the *muon* (μ) and the *tau* (τ) have a charge $q = -1$ and the three neutrinos have $q = 0$. Both quarks and leptons are arranged in three 'families' or 'generations', with the particles in each next generation having a larger mass than those in the previous one. Quarks never appear alone, but they are combined to form the particles called *hadrons*. Hadrons that consist of a quark and a anti-quark, such as e.g. the kaon ($K^+ = u\bar{s}$, $K^0 = d\bar{s}$, $\bar{K}^0 = \bar{d}s$, $K^- = \bar{u}s$) are called *mesons*. Combinations of three quarks and/or anti-quarks are called baryons, such as e.g. the proton (uud) and the neutron (udd).

Four basic forces are known: the gravitational force, the electromagnetic force, the strong force and the weak force. Because of the feeble intrinsic strength of gravity its effects in particle interactions become only important in very extreme conditions such as e.g. on the boundary of a black hole where

Table 1. Gauge bosons and the forces

Gauge boson		Spin	Charge	Mass	Force
photon	γ	1	0	0	electromagnetic
W-boson	$W^{\pm}$	1	$\pm$ 1	80.4 GeV	weak
Z-boson	Z^0	1	0	91.2 GeV	weak
gluons	g	1	0	0	strong
graviton	G	2	0	0	gravitation

the magnitude of the gravitational force reaches extremely high values. We can therefore neglect this force in particle interactions. Hadrons are subject to all four interactions (to the electromagnetic one of course only if they are charged). Leptons do not feel the strong interaction, and since neutrinos are neutral particles these are not subject to electromagnetic interactions either, so that neutrinos interact solely via the weak interaction.

Depending on the force that is acting, the particles involved exchange different force carrying particles that are called intermediate bosons or gauge bosons (Table 1). It is important to note that the elementary particles, i.e. quarks and leptons, all have spin 1/2 and so are fermions, while the force carrying particles have spin 1 (or 2) and are therefore bosons.

The electromagnetic force. This is the force that is presently best understood. It is of infinite range and is reasonably strong. The source of it is electric charge which exists only in quanta and can appear either as positive or negative, leading to an attractive force between unlike charges and a repulsive force between like charges. When electric charges move, qualitatively new phenomena are introduced. A moving charge has associated with it not only an electric field, but also a magnetic field. A test charge will thus be subject to an electric force as well as to a magnetic force, caused by the respective fields. The combined electromagnetic force cannot be described simply by a number representing the magnitude of the force but, instead has to be represented by a vector quantity describing the magnitude of the forces acting in each of the three dimensions of space. When a charge is subject to an acceleration, a variation in electric and magnetic fields is propagated out through space to signal this. If it is subject to regular accelerations the charge emits an electromagnetic wave which is part of the electromagnetic spectrum. Electromagnetic phenomena are described in the classical regime by Maxwell's equations. An interesting feature of these is that they are asymmetric due to the absence of a fundamental quantum of magnetic charge.

The quantum theory for electrodynamics is formulated by describing the interactions of charged particles via the electromagnetic fields as the exchange of the quanta of the field, i.e. the photons, between the particles involved. Quantum electrodynamics QED is the ‘standard’ quantum theory that formed the basis for our understanding of the other forces.

The strong force. The strong force acts on all hadrons, i.e. the particles that are made up of quarks. It is e.g. the force that binds together quarks in hadrons and mesons and also binds together the neutrons and protons within the nucleus. Since the nucleus consists only of positively charged protons and neutral neutrons confined within a very small volume of typically 10^{-15} m diameter, the strong force must be very strongly attractive to overcome the intense mutual repulsion felt by the protons: the binding energy of the strong force between two protons is measured in MeV, as opposed to typical atomic binding energies which are of the order of eV. The strong force is of extremely short range. It may in fact be thought of as acting between two protons only when they are actually touching, implying a range similar to that of the nuclear diameter, i.e. about 10^{-15} m. Finally, the strong force is independent of electric charge, i.e. it does not make a distinction between the proton and the neutron, that can therefore be regarded as different states of a single particle (isospin concept). Because of the pure microscopic nature of the strong force it can only be described accurately using quantum physics.

The theory for the strong force is called quantum chromodynamics (QCD) and was proposed in 1973 by Fritzsch, Leutwyler and Gell-Mann [6]. The basic idea of QCD is to use a new charge, called colour, as the source of the forces between quarks, just as the electric charge is the source of electromagnetic forces between charged particles. The concept of colour (this has nothing to do with the normal meaning of the word colour, but is just a label) was introduced because the suggested quark content of some particles contradicted with the Pauli exclusion principle which states that no two fermions within a given quantum system can have exactly the same quantum numbers. Indeed, some of the particles seemed to contain even three identical quarks; e.g. the doubly charged Δ^{++} particle seemed to consist of three *up* quarks, all with their spin pointing in the same direction. The color hypothesis that was put forward to solve this problem is that each of the three otherwise identical quarks in the Δ^{++} has a different colour assigned to it. The quark model was thus reconciled with the Pauli exclusion principle by introducing the new colour quantum number to differentiate between the quarks. Because particles can consist of up to three quarks, three quark colours were needed to distinguish them uniquely. Thus, as each of the quark types (flavors) must come in three colours, the net effect of the introduction of colour is to triple the number of quarks. The intermediate bosons which are responsible for exchanging the colour charge between particles taking part in strong interaction processes are called gluons.

The weak force. The weak force is the one that is responsible for radioactive decay. Like the strong force it acts over microscopic distances only. In fact, as far as known it makes itself only felt when particles come together at a point (i.e. at a distance of say less than about 10^{-18} m). The first description of the weak interaction was formulated by Fermi in 1934 [7]. One of the most common weak interactions available for study is nuclear beta decay, the simplest manifestation of which is the decay of a free neutron into a proton, an electron and an anti-neutrino

$$n \rightarrow p + e^- + \bar{\nu}_e \ . \tag{1}$$

Fermi therefore took neutron decay as the prototype of the weak interactions, which he then described as four fermions reacting at a single point ('four-fermion point interaction'). Replacing the anti-neutrino by the neutrino, the above reaction is reduced to the symmetric form

$$n + \nu_e \rightarrow p + e^- \ . \tag{2}$$

In analogy to the description for the electromagnetic interaction Fermi then expressed the Hamiltonian (magnitude) for beta decay as a product of two currents, a hadron current $J_H = \bar{\psi}_p \mathcal{O} \psi_n$ and a lepton current $J_L = \bar{\psi}_e \mathcal{O} \psi_\nu$:

$$H \ = \ G_F \, J_H \, J_L \ = \ G_F \, (\bar{\psi}_p \mathcal{O} \psi_n)(\bar{\psi}_e \mathcal{O} \psi_\nu) \ , \tag{3}$$

where ψ_p, ψ_n, ψ_e and ψ_ν are the proton, neutron, electron and neutrino wave functions, respectively. The factor G_F is the so-called Fermi coupling constant which governs the intrinsic strength of the weak interactions, and so the rate of the weak decays, similar to the electric charge e for the electromagnetic interaction. The as yet unknown factors $\mathcal{O}$ (in fact quantum mechanical operators) which multiply the wave functions contain the essence of the weak interaction effects which give rise to the transformations of the particles. The challenge then obviously was to discover the nature of these quantities, i.e. to find out whether they are just numbers (i.e. scalars) or vectors, tensors, etc. This is possible by examining the angles of emission between the outgoing products of beta decay as well their energies. It was not until after the discovery of parity violation in weak interactions - which came as a great surprise since the other interactions were known to conserve parity - that it became clear that the operators $\mathcal{O}$ are a mixture of vector and axial vector quantities. A vector quantity has well-defined properties under a Lorentz transformation (e.g. translations and rotations in space-time). It will e.g. change sign when rotated over 180° and appear again identical when rotated over 360°. An axial vector quantity transforms just like a vector under rotations and translations, but will transform with the opposite sign to a vector under the so-called improper Lorentz transformations such as the parity operation (see further). If the weak interaction is consisting of both vector and axial vector components, which behave differently under a parity transformation, it will thus look different after such a transformation. It turned out that this is exactly what is needed to describe the weak interaction after the observation of parity violation in the beta decay of ^{60}Co by Wu and co-workers [8]. By inserting this form of interaction factor $\mathcal{O}$ into the hamiltonian for beta decay it is then possible to calculate the different features of beta decay processes.

It soon became clear that this four-fermion point-like interaction theory of Fermi is only an approximation. Indeed, it makes e.g. unacceptable predictions for a number of high-energy weak interactions. Of course it can be expected that just like the electromagnetic interaction is transmitted by photons and the strong interaction by gluons, the weak interaction also has its force carrying particles. In the 1960's much work was therefore devoted to the formulation of a theory for the weak interaction similar to QED. This led to the introduction of the so-called intermediate vector bosons $W^{\pm}$ and Z^0. The W^+ and W^- mediate the charged current weak interactions, the Z^0 the neutral current weak interactions. One of the major problems in the development of this theory was the large mass of these W and Z bosons, in contrast to the massless photon. A great triumph was the fact that the W and Z bosons were effectively found in experiments at CERN in 1982 [9]. Soon it was also realized that there are many intimate links between the weak and the electromagnetic interactions. This eventually culminated in 1967/1968, mainly due to the work of Weinberg, Salam and Glashow [10–12], in the formulation of a unified theory for the weak and electromagnetic interactions. This theory describes the interactions of leptons by the exchange of photons, W and Z bosons, and incorporates the so-called Higgs mechanism to generate the masses of these. The finding of the Higgs particle that is related to this mass generating mechanism remains one of the main challenges for particle physics and is currently a major goal at CERN and Fermilab.

Although the unified electroweak theory is much more complete than Fermi's original theory, Fermi's description is still adequate to describe nuclear beta decay processes since the beta decay energy (typically < 10 MeV) is much lower than the mass of the weak interaction gauge bosons ($\simeq 90$ MeV).

The gravitational force. As was mentioned already, the effects of this force are negligible in the context of particle physics. The equivalence between gravitational and inertial mass led Einstein to speculate on the identity of the effects of gravity with those of acceleration, which finally led to his formulation of general relativity.

A successful quantum theory of gravity has not yet been formulated (Einstein spent the last part of his professional career trying to realize this), and the reconciliation of general relativity with quantum theory is one of the major outstanding problems in theoretical physics.

2.2 The Standard Model

The set of quantum theories describing the strong, the electromagnetic and the weak interactions using a 'common' theoretical basis, i.e. QCD and the electroweak theory (including QED), form together the Standard Model for the particles and forces . The gravitational interaction is not included since no quantum theory for gravity exists as yet. Important concepts of the Standard Model are symmetries, local gauge invariance/symmetry (i.e. the fact that some transformations can be applied at each point in space-time independently, always leading to the same result), coupling constants (which determine the amplitudes of physical processes) and spontaneous symmetry breaking. Spontaneous symmetry breaking is any situation in physics in which the state of minimum energy of a physical system is not symmetric under certain transformations of the coordinate system and for which symmetry will be lost when the system evolves towards the state of minimum energy. As an example one can imagine a ball lying on the top of a hill which is surrounded by a deep valley. This is a fully symmetric situation, but when the system goes to its state of minimum energy, i.e. when the ball rolls down the hill and comes to rest somewhere in the valley, the original symmetry of the system with respect to the top of the hill is lost. Another important ingredient of the Standard Model is, finally, the so-called Cabibbo-Kobayashi-Maskawa matrix which relates the quark weak interaction eigenstates to their mass eigenstates.

Symmetries. In physics, and especially in particle physics, symmetries are closely linked to the dynamics of the systems. Symmetry is described by group theory. A group is a collection of elements with specific interrelations defined by group transformations. Repeated transformations between elements of the group should always be equivalent to another group transformation from the initial to the final elements. When a symmetry group governs a particular physical system, i.e. when the Lagrangian (the mathematical expression describing the energy of the system) does not change under the group transformations, this implies the existence of a conserved quantity. More formally, Noether's theorem states that for every continuous symmetry of a Lagrangian there is a quantity that is conserved by its dynamics. A number of symmetries are especially important in the framework of weak interaction studies.

a) Space-time symmetries
   Physical laws are always formulated with respect to a particular origin and coordinate system. However, these laws should remain the same under translations in space and time and rotations about an axis. Noether's theorem then reveals the conserved quantities corresponding to each particular invariance: invariance under a translation in time implies conservation of energy, invariance under a translation in space implies conservation of momentum and invariance under spatial rotations implies conservation of angular momentum.

b) Discrete symmetries
The just discussed continuous space-time symmetries are called proper Lorentz transformations because they can be built up from a succession of infinitesimally small transformations. However, there are also improper symmetries which cannot be built up like this and are often called discrete symmetries. These do not have corresponding conservation laws as important as those of the continuous symmetries but they have been proven to be very useful in guiding us as to which particle reactions are possible with a given force and which not. The most important discrete symmetries are parity or space inversion, charge conjugation and time reversal.

1) Parity
In this operation, denoted P, the system is reflected through the origin of the coordinate system, i.e. $\vec{r} \to -\vec{r}$. The operation is equivalent to a mirror reflection with respect to a plane, followed by a rotation through 180° An alternative way of thinking about the parity operation is as the reversal of a right-handed coordinate system into a left-handed one. If a system is described by a wave function ψ, the parity operation will reverse the sign of the coordinates:

$$P\psi(\vec{r}) = \psi(-\vec{r}) \ . \tag{4}$$

If the system must remain invariant under the parity operation, [i.e. if $V(\vec{r}) = V(-\vec{r})$ in the Schrödinger equation] the observable quantity which must not change is the probability density, which is essentially given by the square of the wave function, so that one must have:

$$\psi(\vec{r})\psi(\vec{r}) = \psi(-\vec{r})\psi(-\vec{r}) \ . \tag{5}$$

So

$$\psi(\vec{r}) = \pm\psi(-\vec{r}) \tag{6}$$

and thus

$$P\psi(\vec{r}) = \pm\psi(\vec{r}) \ . \tag{7}$$

Thus, if the system has to remain invariant under the parity operation the system wave function may either remain unchanged $P\psi = +\psi$, in which case it is said to be an even parity state, or it may change sign $P\psi = -\psi$, in which case the system is said to be an odd parity state. If the forces governing the system respect parity a state with a given parity cannot change into one with the opposite parity.

2) Charge conjugation
Charge conjugation, denoted as C, is the interchange of particles with their anti-particles. If this symmetry holds for a system this means

that the behavior of a set of particles and that of the corresponding set of anti-particles should be exactly the same. For example, a collision between a proton and a neutron should look exactly the same as a collision between an antiproton and an antineutron. As with the parity operation, the wave function of a system may be either even or odd under the charge conjugation operation:

$$C\psi = \pm\psi \,. \tag{8}$$

3) Time reversal
This symmetry, denoted as T, connects a process with the one that is obtained by running backwards in time, i.e. by reversing the directions of motion within the process. Symmetry under the time reversal operation means that if any system can evolve from a given initial state to some final state, then it is possible to start from the final state and produce the initial state again by reversing the directions of motion of all components of the system.

c) Other symmetries
Apart from the above, other conservation laws are also known to exist, such as e.g. the conservation of electric charge, but also of many other quantities in interactions arising from the various forces in nature. Symmetry has also helped us to categorize the particles according to their intrinsic properties, such as e.g. 'strangeness', 'charm', etc.

The CPT Theorem and Broken Symmetries. There are no fundamental reasons to suppose that the individual symmetries should be preserved by the various forces of nature, but it seems a reasonable assumption and was taken for granted for many years, until the discovery of parity violation in weak interactions in 1957. Now we know that the strong and electromagnetic interactions conserve the three discrete symmetries, but that the weak interaction violates both parity and charge conjugation [8], and in addition also violates the combined CP-symmetry (at the 10^{-3} level) [13]. There are, however, good reasons for supposing that the combined CPT symmetry is exact, such that for every process its mirror image, antiparticle and time-reversed process will look exactly as the original process. This is the so-called CPT-theorem. One of the consequences of this theorem is that particles and their anti-particles should have exactly the same masses and lifetimes, as indeed seems to be the case. Another consequence is that if any of the individual symmetries (or a pair of symmetries) is broken, there must be a compensating asymmetry in the remaining operation(s) to cancel it and to ensure exact symmetry under CPT.

2.3 The Cabibbo-Kobayashi-Maskawa Quark-Mixing Matrix

The fermion families

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix} \text{and} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \text{and} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

contain particles with definite mass (unprimed quarks). The fermions defined by the local gauge symmetries of the weak interaction [1, 2] are

$$\begin{pmatrix} u' \\ d' \end{pmatrix}, \begin{pmatrix} c' \\ s' \end{pmatrix} \text{and} \begin{pmatrix} t' \\ b' \end{pmatrix}$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \text{and} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} .$$

The quark states u', d', c', s', t', b' are eigenstates of the weak interaction, while the states u, d, c, s, t, b are the mass eigenstates of the flavor-conserving strong interaction. If we were to ignore the masses of the particles and focus on the symmetries, each of the three families would look exactly the same. In other words, the u', c' and t' would look and behave exactly the same in all interactions, and so would their partners, the d', s' and b'. The same would be true for the charged leptons e, μ and τ and their partners, the ν_e, ν_μ and the ν_τ. In fact if the local gauge symmetry of the weak force were exact, the quarks and leptons would all be massless. But in reality particles do have mass, and because of this a symmetry violating mechanism, known as the Higgs mechanism, was built in to the Standard Model. Although this allows to explain the masses of the electroweak gauge bosons, it remains a mystery why the quarks and leptons have the masses we observe. Another mystery is the fact that the mass states of the quarks (i.e. the unprimed quarks) are not the same as their weak states (primed quarks). The weak force seems to have some kind of 'skewed' vision that produces quarks and acts on quarks that are mixtures of the mass states from the different families. Equivalently, the symmetry-breaking mechanism that gives the quarks their masses mixes the quark weak states to create mass states. The weak interaction thus rotates quark states. Most of the quark mixing occurs between the first two families. The exact amounts of mixing are not given by theory but instead have to be determined experimentally and form the numbers in the so-called Cabibbo-Kobayashi-Maskawa (CKM) matrix [15,16], the unitary matrix that rotates

[1] Local gauge symmetries (cf. Sect. 1.2) provide the guiding principles in the construction of the Standard Model.

[2] We neglect here the mixing between the neutrinos that follows from the recent discovery of neutrino oscillations (see e.g. [14]), and thus take the weak eigenstates and the mass eigenstates of the leptons to be identical to each other.

the complete set of quark mass states into the complete set of quark weak states and vice versa. Since the weak force always acts between the two members of a given family, all mixing can be placed into one of the partners of each family. By convention, all the mixing is then placed in the lightest members of the three families, i.e. the d, s, and b quarks are mixtures of d', s' and b'. It follows that the weak states and the mass states for the other members of the quarks families are equivalent, i.e. $u = u'$, $c = c'$ and $t = t'$. It should be stressed though that no matter which way one views the quark mixing, the quarks that transmute into each other by the action of the W boson are *always* the weak states.

In terms of the Cabibbo-Kobayashi-Maskawa matrix V the mixing between the different quark flavors is given by

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} . \tag{9}$$

There are several parameterizations of the CKM matrix [17]. The 'standard' one utilizes the so-called Cabibbo angles $\theta_{12}, \theta_{23}, \theta_{13}$ and a phase δ_{13}

$$V \cong \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \tag{10}$$

with $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$ for the "generation" labels $i, j = 1, 2, 3$. In this parametrization the rotation angles are defined and labelled in a way which relates to the mixing of two specific generations, and if one of these angles vanishes, so does the mixing between those two generations.

The present 90% confidence limits on the magnitude of the elements of the CKM matrix are [17]:

$$V \cong \begin{pmatrix} 0.9741 - 0.9756 & 0.219 - 0.226 & 0.0025 - 0.0048 \\ 0.219 - 0.226 & 0.9732 - 0.9748 & 0.038 - 0.044 \\ 0.004 - 0.014 & 0.037 - 0.044 & 0.9990 - 0.9993 \end{pmatrix} , \tag{11}$$

with $e^{\pm i\delta_{13}} \cong 1$ it follows from the observed values of V_{ub}, V_{ud} and V_{ts} that $s_{13} \cong s_{23} \cong 0$ (i.e. $\theta_{13} \cong \theta_{23} \cong 0$), so that $c_{13} \cong c_{23} \cong 1$ and the matrix reduces to

$$V \cong \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} . \tag{12}$$

The third generation thus decouples and the situation reduces to the mixing between the first two generations that was originally described by Cabibbo [15], with $\theta_{12} \equiv \theta_c$ the original Cabibbo angle:

$$|d'\rangle = \cos\theta_c|d\rangle + \sin\theta_c|s\rangle , \tag{13a}$$

$$|s'\rangle = -\sin\theta_c|d\rangle + \cos\theta_c|s\rangle . \tag{13b}$$

An illustrative way to show the effect of quark mixing is to compare the strength of neutron decay

$$n \rightarrow p + e^- + \bar{\nu}_e \tag{14}$$

with that of muon decay

$$\mu^- \rightarrow e^- + \bar{\nu}_\mu + \bar{\nu}_e \ . \tag{15}$$

Since both are charged current weak interaction processes one would expect their strength to be identical. Muon decay being a purely leptonic process its strength is entirely determined by the intrinsic strength G_F (Fermi coupling constant) of the weak interaction, i.e. $G_\mu = G_F$, which is obtained from measurements of the muon lifetime. Since neutron decay, or in general nuclear beta decay, is a so-called semi-leptonic process (involving both leptons and quarks), its strength is affected by the weak interaction between the quarks as well. Indeed, since the proton and neutron are made up of *up* and *down* quarks, the mixing of these will affect the decay strength. Thus $G_\beta \equiv G_V = G_F V_{ud}$, with G_V the weak interaction strength in beta decay (which is determined most precisely from the average $\mathcal{F}$t-value of the well-studied set of nine superallowed $0^+ \rightarrow 0^+$ beta transitions [18]) and with V_{ud} taking into account the effect of the mixing of the *up* and *down* quarks. Then

$$G_\beta^2/G_\mu^2 = {G_V}^2/{G_F}^2 = \frac{1.2906(13) \times 10^{-10} GeV^{-4}}{1.36047(2) \times 10^{-10} GeV^{-4}} = 0.9486(10) = V_{ud}^2 \ . \tag{16}$$

The about 5% 'missing' weak interaction strength in nuclear beta decay cannot be lost of course. It is instead found in the beta decay of the Λ-particle: $\Lambda(usd) \rightarrow p(uud) + e^- + \bar{\nu}_e$ (Fig. 1).

2.4 Not the Ultimate Theory

Although the Standard Model has proven to be highly successful in describing all particle interaction processes observed till know with good accuracy, it is nevertheless believed not to be the ultimate theory of forces and particles. Indeed there are still a number of fundamental problems related to it. We will only mention some of the most prominent ones here: Are the quarks and leptons really the most fundamental particles? Why do they both seem to come in three generations? Are there more than three generations? Why is parity violated in the weak interaction and what is the mechanism behind this violation? The Higgs-mechanism successfully predicts the masses of the photon, the W and the Z bosons, but what is the mass of the Higgs boson itself? What causes the quarks and leptons to have the masses we observe? How to unify the gravitational force with the three other ones? Are there more than four basic forces? ... In addition to all this it is generally felt

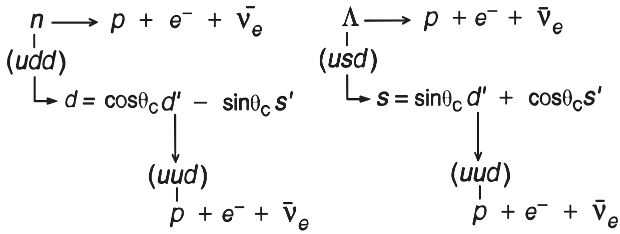

Fig. 1. In beta decay, the neutron transforms into a proton through the transition $d \to u$, and the Λ transforms into a proton through the transition $s \to u$. However, in both cases, the W acts between the weak quark states of the first family, that is, the W causes the transition $d' \to u$. So only the fraction of the d quark in the state d' (according to the CKM matrix this amplitude is given by the matrix element $V_{ud} \simeq \cos\theta_c$) takes part in neutron decay, and only the fraction of the s in the state d' (this amplitude is proportional to $V_{us} \simeq \sin\theta_c$) takes part in the decay of the Λ. The neutron and Λ decay probabilities are proportional to the square of the amplitudes. From [19].

as unsatisfactory that the Standard Model involves about 20 fundamental ‘parameters’, the value of which is not given by the model itself but has to be determined by experiment, e.g. the fine structure constant α, the Fermi coupling constant G_F, the quark and lepton masses, the Higgs-particle mass, three mixing angles and a phase in the CKM matrix, etc.

Because of this, the Standard Model is believed to be only the ‘low-energy’ approximation of a more fundamental theory, which nevertheless yields reliable predictions for interaction processes up to energies of about 200 GeV, i.e. the highest currently accessible energy scale. The Standard Model can thus be considered with respect to this more fundamental theory such as e.g. Newtonian mechanics with respect to the theory of Special Relativity or as classical gravity described by Newton’s law with respect to General Relativity. The challenge then of course consists in finding indications for new physics (and the new gauge bosons related to it) that would indicate in which direction the Standard Model has to be extended to obtain a more complete model. This can be done either at colliders (such as those at the large international accelerator centers like e.g. CERN, Fermilab and DESY), where one can search for the direct production of as yet unknown intermediate bosons and new phenomena, or in non-accelerator experiments (e.g. the large neutrino detectors that were built during the last decades) and in nuclear beta decay. In the last case precision experiments have to be performed to search for tiny deviations from the Standard Model predicted values for certain observables, which can be caused by the presence of new gauge bosons and new interactions. Searches for physics beyond the Standard Model have recently been successful with the finding of neutrino oscillations (see. e.g. [14]).

3 Nuclear Beta Decay

3.1 Selection Rules

In order not to complicate things unnecessarily we will restrict here to the so-called allowed approximation for nuclear beta decay. In this approximation the nucleons are treated non-relativistically while the lepton wave functions are evaluated at the origin, i.e. it is assumed that the leptons are created at $\vec{r} = 0$ and that the lepton wave functions are constant across the nuclear volume. It follows that in this case the total orbital angular momentum of the leptons $\ell = 0$, corresponding to s-wave emission of the lepton pair. The total angular momentum change must then be provided by appropriate alignment of the two lepton spins of $1/2\,\hbar$. In transitions such as $0^+ \to 0^+$ transitions, with $\Delta I = 0$, the β-particle and the neutrino are emitted with their spins anti-parallel. Such transitions are called Fermi transitions. For transitions with $\Delta I = 0, \pm 1$ (except $0 \to 0$), such as e.g. $1^+ \to 0^+$, the lepton spins are parallel and these are called Gamow-Teller transitions. Note that in addition to these spin selection rules similar isospin selection rules apply (i.e. $\Delta T = 0$ for Fermi transitions and $\Delta T = 0, \pm 1$ for Gamow-Teller transitions). The allowed character of the transitions in addition implies that there can be no parity change between the initial and final states, i.e. $\pi_i\,\pi_f = +$.

3.2 The Beta Decay Interaction Hamiltonian

As was mentioned already, beta decay can be described in a way that is very similar to the electromagnetic interaction. The electromagnetic interaction density between a current $e\,j_\mu$ and the radiation field described by a vector potential A_μ, is given by:

$$H = \sum_n e\mathbf{j}_\mu(\vec{\mathbf{r}}_\mathbf{n}).\mathbf{A}_\mu(\vec{\mathbf{r}}_\mathbf{n}) \tag{17}$$

where $\mathbf{r_n}$ is the position of the n^{th} particle. The strength of the interaction is determined by the electric charge e. In a quantum-mechanical treatment, the transition current is given by:

$$j_\mu \;=\; \bar{\psi}_f\,\gamma_\mu\,\psi_i \tag{18}$$

where ψ_i and ψ_f are the wave functions of the initial and final state, respectively, and γ_μ is a Dirac γ-matrix.

The γ-matrices are 4×4 matrices that are given by:

$$\gamma_k = \begin{pmatrix} 0 & -\mathrm{i}\sigma_k \\ \mathrm{i}\sigma_k & 0 \end{pmatrix}, \qquad k = 1,2,3 \tag{19}$$

$$\gamma_4 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix} \tag{20}$$

$$\gamma_5 = \gamma_1\gamma_2\gamma_3\gamma_4 = \begin{pmatrix} 0 & -I \\ -I & 0 \end{pmatrix}$$

where the σ_k are the 2 × 2 Pauli spin matrices [3]

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma_2 = \begin{pmatrix} 0 & -\mathrm{i} \\ \mathrm{i} & 0 \end{pmatrix}, \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \tag{21}$$

and I is the 2 × 2 unit matrix.

The γ-matrices obey the relations

$$\gamma_\nu \gamma_\mu = -\gamma_\mu \gamma_\nu, \qquad \nu \neq \mu \tag{22}$$
$$\gamma_5 \gamma_\mu = -\gamma_\mu \gamma_5,\ \mu = 1,2,3,4 \tag{23}$$
$$\gamma_\mu^2 = \gamma_5^2 = 1\ . \tag{24}$$

Fermi constructed the beta decay interaction density in analogy to the above equation:

$$H = \sum_n g_F\, J_\mu(\vec{r}_n).L_\mu(\vec{r}_n) \tag{25}$$

where J_μ is the current associated with the neutron-proton transition and L_μ is the "vector potential" of the emitted lepton field. Again one must sum over all particles, i.e. the nucleons in the nucleus. Analogous to the electric charge e which determines the strength of electromagnetic interactions, Fermi introduced the "elementary charge" g_F $(= G_F/\sqrt{2})$ determining the strength of the beta interaction. These elementary charges are usually called the "coupling constants" as they characterize the coupling between the field and its sources.

For J_μ one has a similar expression as for j_μ :

$$J_\mu = \bar{\psi}_p\, \mathcal{O}_i\, \psi_n \tag{26}$$

with $\mathcal{O}_i$ the operator. It can be shown that the lepton potential L_μ must be of the same form in order to make H relativistically invariant:

$$L_\mu = \bar{\psi}_e\, \mathcal{O}_i\, \psi_\nu\ . \tag{27}$$

The beta interaction is thus obtained by multiplying two terms of the type $\bar{\psi}_a\, \mathcal{O}_i\, \psi_b$. The operator $\mathcal{O}_i$ can be expressed as various combinations of Dirac γ-matrices and it can be shown that there are 16 linear independent terms which can be grouped into five classes according to their transformation properties (Table 2). The beta decay observables (i.e. the transition probabilities and therefore the matrix elements) have to be Lorentz invariant, which implies that H_i should become a scalar or a pseudoscalar.

A scalar, i.e. the result of the scalar product of two vectors such as the product $\vec{p}.\vec{q}$ of the momenta $\vec{p}$ and $\vec{q}$ of the β-particle respectively the neutrino

[3] Note that a different representation of the Pauli- and γ-matrices can lead to different sign conventions for the C-coupling constants

Table 2. The different operators that can act in the weak interaction hamiltonian and their transformation properties.

Operator O_i	Number of independent matrices	Relativistic transformation properties of $\bar{\psi}_a\,\mathcal{O}_i\,\psi_b$
1	1	**S**calar
γ_μ	4	**V**ector
$\gamma_\mu\gamma_\lambda$	6	antisymmetric **T**ensor of rank 2
$\gamma_\mu\gamma_5$ $(=\gamma_\nu\gamma_\lambda\gamma_\sigma)$	4	**A**xial vector
γ_5 $(=\gamma_1\gamma_2\gamma_3\gamma_4)$	1	**P**seudoscalar

emitted in β-decay, does not change sign under the parity operation (both $\vec{p}$ and $\vec{q}$ change sign, leaving their scalar product invariant). A pseudoscalar quantity, i.e. the scalar product of a normal vector and an axial vector, on the contrary does change sign under the parity operation. An example is the longitudinal polarization $\vec{\sigma}.\vec{p}$ of a beta particle (with $\vec{\sigma}$ its spin vector and $\vec{p}$ its momentum). Since a momentum vector ($\vec{p}$) changes sign under the parity operation and a angular momentum vector ($\vec{\sigma}$) does not, the scalar product $\vec{\sigma}.\vec{p}$ changes sign under parity.

It is easily seen that in order to obtain either a scalar or a pseudoscalar when multiplying the leptonic and the hadronic currents in the beta decay hamiltonian, the operators between the nucleon and lepton wave functions must be identical, apart from a factor γ_5 (pseudoscalar), and hence only the combinations for J_μ and L_μ listed in Table 3 are possible. Using the trans-

Table 3. Possible interaction type combinations for J_μ and L_μ

J_μ	L_μ
S	S or P
V	V or A
T	T
A	A or V
P	P or S

formation properties of the Dirac γ-matrices this can be easily checked by calculating the respective products of the different operators, e.g. for the product $V.T$ one gets $\gamma_\mu \gamma_\lambda \gamma_\sigma = \gamma_\nu \gamma_5$ which is an axial vector and therefore not possible; for $T.T$ one gets $\gamma_\mu \gamma_\lambda \gamma_\nu \gamma_\sigma = \gamma_5$ which is possible as it is a pseudoscalar quantity, etc. According to the transformation property of $\bar{\psi}_a \, \mathcal{O}_i \, \psi_b$ one speaks of Scalar (S), Vector (V), Tensor (T), Axial vector (A) or Pseudoscalar (P) type weak interactions. A priori there is no reason why either one of these interactions should be preferred and one can expect that the interaction found in nature is an arbitrary linear combination of all five interactions:

$$H = \sum_i H_i \tag{28}$$

with

$$H_i = g_i(\bar{\psi}_p \, \mathcal{O}_i \, \psi_n)(\bar{\psi}_e \, \mathcal{O}_i \, \psi_\nu) + h.c. \tag{29}$$

and $g_i = g_F C_i$ $(i = S, V, T, A, P)$.

Five different coupling constants have to be introduced since the phenomenological theory does not permit any conclusion about the strength of the five interactions. The factor g_F is the overall strength (coupling constant) of the weak interaction, but it is not excluded that e.g. a vector type interaction has a different strength then e.g. a tensor type weak interaction, etc. The coupling constants C_i which were introduced thus define the relative strength of the different possible weak interaction types. It is hoped that the g_i are fundamental constants and do not depend on the specific nuclear properties. This has indeed been proven to be the case. The values of the coupling constants C_i have to be determined by experiment.

The interaction density H_i can have different forms. Indeed, with the requirement that the product $J_\mu L_\mu$ should result in either a scalar or a pseudoscalar, the following interaction densities can be formed:

$$H_i^{even} = g_i(\bar{\psi}_p \, \mathcal{O}_i \, \psi_n)(\bar{\psi}_e \, \mathcal{O}_i \, \psi_\nu) + h.c. \tag{30}$$

or

$$H_i^{odd} = g_i'(\bar{\psi}_p \, \mathcal{O}_i \, \psi_n)(\bar{\psi}_e \, \mathcal{O}_i \gamma_5 \, \psi_\nu) + h.c. \tag{31}$$

with $g_i' = g_F C_i'$ and $i = S, V, T, A, P$.

The superscripts *even* and *odd* refer to the behavior under the parity operation. Indeed, $< H_{even} > = scalar$ and $< H_{odd} > = pseudoscalar$. Note that one could also write

$$g_i''(\bar{\psi}_p \, \mathcal{O}_i \gamma_5 \, \psi_n)(\bar{\psi}_e \, \mathcal{O}_i \gamma_5 \, \psi_\nu) + h.c. \; , \tag{32}$$

but since $\gamma_5 \gamma_5 = 1$ this is identical to H_{even}. If both kinds of interaction contribute to beta transitions one obtains interference terms $H_i^{even} H_i^{odd}$ which are not invariant with respect to space inversion. Indeed one would then have (with λ_β the total decay rate):

$$\lambda_\beta = \mid \langle H_{int} \rangle|^2 \simeq |scalar + pseudoscalar|^2 \ . \tag{33}$$

Upon reversal of the axes : $(x, y, z) \to (-x, -y, -z)$ this changes to:

$$\lambda_\beta = \mid \langle H_{int} \rangle|^2 \simeq |scalar - pseudoscalar|^2 \tag{34}$$

and λ_β would thus not be parity-invariant. Originally one thought that the weak interaction was, as the strong and the electromagnetic interaction, parity invariant and that therefore one could only have H_i^{even} or H_i^{odd} but not a combination of both. After the discovery that parity is violated in the weak interaction it followed that the coexistence of scalar and pseudoscalar terms is needed to allow the violation of reflection invariance. The generalized form of the Hamiltonian is then:

$$H = \sum_i (H_i^{even} + H_i^{odd}) + h.c. \ . \tag{35}$$

More explicitly this generalized Hamiltonian can be written as :

$$H = g_F \sum_i (\bar{\psi}_p \, \mathcal{O}_i \, \psi_n)(\bar{\psi}_e \, \mathcal{O}_i \, (C_i + C_i^{'} \gamma_5) \, \psi_\nu) + h.c. \tag{36}$$

or in detailed form :

$$\begin{aligned} H_\beta = \frac{G_F}{\sqrt{2}} V_{ud} & \left[\left(\bar{\psi}_p \psi_n \right) \left(\bar{\psi}_e \left(C_S + C_S' \gamma_5 \right) \psi_\nu \right) \right. \\ & + \left(\bar{\psi}_p \gamma_\mu \psi_n \right) \left(\bar{\psi}_e \gamma^\mu \left(C_V + C_V' \gamma_5 \right) \psi_\nu \right) \\ & + \frac{1}{2} \left(\bar{\psi}_p \sigma_{\lambda\mu} \psi_n \right) \left(\bar{\psi}_e \sigma^{\lambda\mu} \left(C_T + C_T' \gamma_5 \right) \psi_\nu \right) \\ & - \left(\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n \right) \left(\bar{\psi}_e \gamma^\mu \gamma_5 \left(C_A + C_A' \gamma_5 \right) \psi_\nu \right) \\ & \left. + \left(\bar{\psi}_p \gamma_5 \psi_n \right) \left(\bar{\psi}_e \gamma_5 \left(C_P + C_P' \gamma_5 \right) \psi_\nu \right) \right] \\ & + h.c. \end{aligned} \tag{37}$$

with $i = S, V, T, A, P$ and

$$\sigma_{\lambda\mu} = -\frac{1}{2} i \left(\gamma_\lambda \gamma_\mu - \gamma_\mu \gamma_\lambda \right) . \tag{38}$$

There are thus 10 coupling constants.

In order to be able to use (37) for the description of nuclear β-decay where also other nucleons than just the one that is involved in the β-decay are present in the nucleus, the so-called form factors that are induced due to nuclear structure effects [20] (and which are not included yet in 37) have to be negligible. In the following we will assume this to be the case, and restrict also to allowed β-decay. It is further also assumed that the kinematic effects of the masses of the neutrinos that can be produced in β-decay are negligible and that only one neutrino state is involved.

All coupling constants C_i and C_i' are in principle complex numbers and invariance under time-reversal requires that they are all real. The ratios C_i/C_i' determine the helicity properties of the different interaction types. Parity is not violated if either $C_i = 0$ or $C_i' = 0$, i.e. if only one type is present. Parity is violated if both $C_i \neq 0$ and $C_i' \neq 0$. Maximum parity violation is reached for $|C_i| = |C_i'|$. Charge-conjugation invariance holds if the C_i are real and the C_i' are purely imaginary, up to an overall phase.

The Standard Model corresponds to $C_V = C_V' = 1$ and $C_A = C_A'$, all other coupling constants being zero. The pseudoscalar contribution vanishes to lowest order for beta decay since $\mathcal{O}_P = \gamma_5$ couples large to small components of the nuclear wave functions and thus the hadronic matrix element with $\mathcal{O}_P$ in the above hamiltonian is very small. The S- and V-interactions lead to Fermi-transitions, the A- and T-interactions to Gamow-Teller transitions.

3.3 Angular Distribution and Correlations in Beta Decay

Due to the different couplings of V, A, S and T interaction the angular correlations in β-decay depend on the coupling constants C_i and C_i'. For the general interaction of (37) the distribution in electron and neutrino directions and electron polarization and energy for an allowed β-transition from oriented nuclei is given by (only the most important terms are included here) [21]:

$$\begin{aligned}
&\omega(\langle\vec{I}\rangle, \vec{\sigma}|E_e, \Omega_e, \Omega_\nu) dE_e d\Omega_e d\Omega_\nu \propto \\
&F(\pm Z, E_e) p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu \times \\
&\xi \left\{ 1 + \frac{\vec{p_e} \cdot \vec{p_\nu}}{E_e E_\nu} a + \frac{m}{E_e} b + \right. \\
&\frac{\vec{I}}{I} \cdot \left[\frac{\vec{p_e}}{E_e} A + \frac{\vec{p_\nu}}{E_\nu} B + \frac{\vec{p_e} \times \vec{p_\nu}}{E_e E_\nu} D \right] + \\
&\left. \vec{\sigma} \cdot \left[\frac{\vec{p_e}}{E_e} G + \frac{\langle\vec{I}\rangle}{I} N + \frac{\vec{p_e}}{E_e + m} \left(\frac{\langle\vec{I}\rangle}{I} \cdot \frac{\vec{p_e}}{E_e} \right) Q + \frac{\langle\vec{I}\rangle}{I} \times \frac{\vec{p_e}}{E_e} R \right] \right\}
\end{aligned} \tag{39}$$

where E, p and Ω denote the total energy, momentum and angular coordinates of the beta particle and the neutrino, $\langle\vec{I}\rangle$ is the nuclear polarization of the state with spin I, E_0 is the total energy at the spectrum endpoint, m is the rest mass of the electron, $\vec{\sigma}$ is the spin vector of the β-particle and $F(\pm Z, E_e)$ is the Fermi-function which takes into account the interaction between the β-particle and the nuclear charge. The upper (lower) sign refers to β^- (β^+)-decay. Experiments observing these correlations allow to determine the so-called correlation coefficients a (beta-neutrino correlation), b (Fierz interference term), A (beta asymmetry), B (neutrino asymmetry), G (longitudinal beta polarization), D (D-triple correlation), R (R-triple correlation), etc. which depend (as does the factor ξ) only on the nuclear matrix elements of the observed β-transition and on the coupling constants C_i and $C_i^{'}$. Note that two basic properties of the weak interaction were determined from measurements of these correlations in β-decay: the violation of parity, which was first observed in a measurement of the β-asymmetry parameter (A) in the decay of ^{60}Co [8] and the $V - A$ structure of the weak interaction, which was deduced from $\beta\nu$-correlation (a) measurements on a series of noble gas nuclei [22].

Explicit expressions for the correlation coefficients, including the Coulomb corrections, can be found in [21]. As an example and for ease of discussion we list here the expressions for the $\beta\nu$-correlation coefficient a, the Fierz interference term b and the β-asymmetry parameter A:

$$\begin{aligned}\xi = &|M_F|^2 \left(|C_S|^2 + |C_V|^2 + |C_S'|^2 + |C_V'|^2\right) \\ &+|M_{GT}|^2 \left(|C_T|^2 + |C_A|^2 + |C_T'|^2 + |C_A'|^2\right)\end{aligned} \tag{40}$$

$$\begin{aligned}a\xi = &|M_F|^2 \left[-|C_S|^2+|C_V|^2 - |C_S'|^2+|C_V'|^2 \mp 2\frac{\alpha Z m}{p_e} Im\left(C_S C_V^* + C_S' C_V'^*\right)\right] \\ &+\frac{|M_{GT}|^2}{3}\left[|C_T|^2 - |C_A|^2 + |C_T'|^2 - |C_A'|^2 \pm 2\frac{\alpha Z m}{p_e} Im\left(C_T C_A^* + C_T' C_A'^*\right)\right]\end{aligned}$$

$$\begin{aligned}b\xi = &\pm 2\gamma Re\left[|M_F|^2\left(C_S C_V^* + C_S' C_V'^*\right)\right. \\ &\left.+|M_{GT}|^2\left(C_T C_A^* + C_T' C_A'^*\right)\right]\end{aligned} \tag{41}$$

$$\begin{aligned}A\xi = &|M_{GT}|^2 \lambda_{I'I}\left[\pm 2Re\left(C_T C_T'^* - C_A C_A'^*\right) + 2\frac{\alpha Z m}{p_e} Im\left(C_T C_A'^* + C_T' C_A^*\right)\right] \\ &+\delta_{I'I} M_F M_{GT}\sqrt{\frac{I}{I+1}}\left[2Re\left(C_S C_T'^* + C_S' C_T^* - C_V C_A'^* - C_V' C_A^*\right)\right. \\ &\left.\pm 2\frac{\alpha Z m}{p_e} Im\left(C_S C_A'^* + C_S' C_A^* - C_V C_T'^* - C_V' C_T^*\right)\right] .\end{aligned} \tag{42}$$

In these equations M_F (M_{GT}) are the Fermi (Gamow-Teller) matrix elements, $\gamma = \sqrt{1-(\alpha Z)^2}$ with α the fine structure constant and Z the atomic number of the daughter nucleus, I and I' are the angular momenta of the initial and the final nuclear states, $\delta_{I'I}$ is the Kronecker delta symbol and

$$\lambda_{I'I} = \begin{cases} 1 & I \rightarrow I' = I - 1 \\ \dfrac{1}{I+1} & I \rightarrow I' = I \\ -\dfrac{I}{I+1} & I \rightarrow I' = I + 1 \end{cases} \tag{43}$$

Note that if a pure Fermi or a pure Gamow-Teller transition is used, the correlation coefficients become independent of the nuclear matrix elements and thus allow to determine the coupling constants independent of any nuclear structure effects.

The values of the coupling constants, which tell us which of the four possible interaction types (i.e. scalar, vector, tensor, and axial-vector) contribute to beta decay, can thus be extracted from the measurement of one or more of the relevant correlation coefficients. Frequently, for a given correlation coefficient complementary information can be obtained from the main part of the coefficient and from its Coulomb corrections (i.e. the terms of order α). E.g. in the β-asymmetry parameter A (42) the Coulomb correction terms will only be present if the coupling constants have an imaginary part and hence probes time reversal violation. However, these Coulomb corrections typically contribute to the correlation coefficients at the level of a few percent only.

To see more easily the sensitivity of the different correlation coefficients to new physics (i.e. scalar and/or tensor type weak interactions, a right-handed V,A-interaction, etc.) as well as for the planning of experiments and a first interpretation of new data it is often useful to work with approximate expressions. These equations are usually accurate to the few permille level or even better. We will illustrate this here for searches for scalar and tensor components in the weak interaction. To develop the approximate expressions in this case, maximal parity violation and time reversal invariance for the V- and A-interactions is assumed, i.e. $C'_V = C_V$, $C'_A = C_A$ and C_V and C_A real. One then has

$$\xi = 2\left[|M_F|^2 C_V^2 + |M_{GT}|^2 C_A^2\right] \tag{44}$$

and for a pure Fermi transition the $\beta\nu$-correlation coefficient a can be written as

$$a_F \simeq 1 - \frac{|C_S|^2 + |C'_S|^2}{C_V^2} \mp \frac{\alpha Z m}{p_e} Im\left(\frac{C_S + C'_S}{C_V}\right) , \tag{45}$$

while for a pure Gamow-Teller transition

$$a_{GT} \simeq -\frac{1}{3}\left[1 - \frac{|C_T|^2 + |C'_T|^2}{C_A^2} \mp \frac{\alpha Z m}{p_e} Im\left(\frac{C_T + C'_T}{C_A}\right)\right] . \tag{46}$$

Note that the highest sensitivity to terms containing scalar and/or tensor type coupling constants is always obtained for pure transitions. This holds for all correlation coefficients. Further, the sensitivity to terms with $\alpha Z m/p_e$ can be optimized by selecting β-transitions with a low endpoint energy from heavy nuclei.

The Fierz interference term $b' \equiv bm/E_e$ is for a pure Fermi transition approximated as

$$b'_F \simeq \pm\frac{\gamma m}{E_e} Re\left(\frac{C_S + C'_S}{C_V}\right) \tag{47}$$

and for a pure Gamow-Teller transition

$$b'_{GT} \simeq \pm \frac{\gamma m}{E_e} Re \left(\frac{C_T + C'_T}{C_A} \right) . \tag{48}$$

Since this Fierz term depends only on scalar and tensor coupling constants, it is zero in the Standard Model. Further, because of the factor $\gamma m / E_e$ the sensitivity of it to a scalar or tensor type weak interaction can be optimized by observing low-energy transitions from light nuclei. Further, as b depends only on the energy of the emitted β-particle but does not contain any particular directional dependence, a measurement of any correlation coefficient will always include b' such that a measurement of a correlation coefficient X will in fact yield the quantity

$$\widetilde{X} \equiv \frac{X}{1 + b'} . \tag{49}$$

Given the present experimental accuracy for b' (e.g. [18]) this becomes important for measurements where a precision of 1% or better is reached.

With the same assumptions as above, the β-asymmetry parameter A can be written as

$$A \simeq \frac{\mp \lambda_{I'I} \rho^2 - 2\delta_{I'I} \sqrt{\frac{I}{I+1}} \rho}{1 + \rho^2} + \frac{\alpha Z m}{p_e} \left[\frac{\lambda_{I'I} \rho^2 \pm \delta_{I'I} \sqrt{\frac{I}{I+1}} \rho}{1 + \rho^2} Im \left(\frac{C_T + C'_T}{C_A} \right) \pm \frac{\delta_{I'I} \sqrt{\frac{I}{I+1}} \rho}{1 + \rho^2} Im \left(\frac{C_S + C'_S}{C_V} \right) \right] \tag{50}$$

with

$$\rho = \frac{C_A M_{GT}}{C_V M_F} . \tag{51}$$

Note that the first term in (50) gives the Standard Model value for A for a given transition and that A is sensitive to scalar and tensor currents only through the Coulomb terms. For a pure Fermi transition $A = \widetilde{A} \equiv 0$, while for a pure Gamow-Teller transition one gets (using (48)-(50))

$$\widetilde{A_{GT}} \equiv \frac{A_{GT}}{1 + b'} \simeq \lambda_{I'I} \left[\mp 1 + \frac{\alpha Z m}{p_e} Im \left(\frac{C_T + C'_T}{C_A} \right) + \frac{\gamma m}{E_e} Re \left(\frac{C_T + C'_T}{C_A} \right) \right] \tag{52}$$

where A_{GT} is obtained from (50) by inserting $y \equiv 1/\rho = 0$.

Finally, it is to be noted that the integral of the transition probability ω defined by (39) over all energies and angles does not contain any angular dependence anymore but simply yields the inverse lifetime τ^{-1}:

$$\frac{1}{\tau} \equiv \int \omega \left(\langle \vec{I} \rangle, \vec{\sigma} | E_e, \Omega_e, \Omega_\nu \right) dE_e d\Omega_e d\Omega_\nu = \int \frac{G_\beta^2}{(2\pi)} \xi F(\pm Z, E_e) p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu \ . \qquad (53)$$

From this the comparative half-life or ft-value is obtained as

$$ft = \frac{2K}{G_F^2 V_{ud}^2 \xi} \qquad (54)$$

with

$$t = t_{1/2} \left[\frac{1 + \epsilon/\beta^+}{BR} \right] \ . \qquad (55)$$

the reduced half-life, ϵ/β^+ the electron capture to positron ratio and BR the branching ratio of the β-transition. Further,

$$\frac{K}{(\hbar c)^6} = \frac{2\pi^3 \hbar \ln 2}{(m_e c^2)^5} = 8120.271(12) \times 10^{-10}\, GeV^{-4}\, s \qquad (56)$$

and

$$f = \int F(\pm Z, E_e) p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu \qquad (57)$$

is the so-called statistical rate function.

The value for the Fermi coupling constant G_F is known from the purely leptonic decay of the muon [17]

$$\frac{G_F}{(\hbar c)^3} = 1.16639(1) \times 10^{-5}\, GeV^{-2} \ . \qquad (58)$$

It is related to the vector coupling constant G_V in nuclear beta-decay by $G_\beta \equiv G_V = G_F\, V_{ud}\, g_V(q^2 \to 0)$, with g_V the vector form factor and $g_V(q^2 \to 0) \equiv C_V = 1$ the vector coupling constant with q the momentum transfer to the leptons in the decay.

Including now also radiative corrections and isospin symmetry breaking corrections (that are not included in the equations given by [21]) and using (44) for the factor ξ one gets

$$ft = \frac{2K}{G_F^2 V_{ud}^2} \frac{1}{(1 + \delta_R)\, 2 \left[M_F^2 C_V^2 \,(1 - \delta_c) \left(1 + \Delta_R^V\right) + M_{GT}^2 C_A^2 \left(1 + \Delta_R^A\right) \right]} \qquad (59)$$

with δ_R, respectively Δ_R the nucleus-dependent and nucleus-independent radiative corrections and δ_c the isospin symmetry-breaking correction. All these corrections are of the order of 0.5% to a few percent (see e.g. [23,18].

More details on the formalism for weak interaction studies in nuclear and neutron β-decay as well as explicit expressions for other observables than the ones that were discussed here can be found in [1].

4 Searching for Non-standard Model Physics in Nuclear β-Decay

All experiments that were carried out till now can be explained by a time reversal invariant pure V-A interaction with maximal violation of parity. Nevertheless, experimental error bars still leave sufficient room for the possible existence of other types of weak interaction in beta decay, e.g. scalar or tensor type interactions or a right-handed V,A-interaction. In the next sections we will describe a number of previous as well as ongoing experiments to illustrate how measurements in nuclear beta decay provide valuable information about the properties of the weak interaction. Such experiments search for the possible presence of e.g. right-handed currents, scalar or tensor currents and time reversal violation or determine the V_{ud} Cabibbo-Kobayashi-Maskawa matrix element. In addition, they provide constrains on a wide range of extensions of the Standard Model, such as e.g. models involving leptoquarks [62].

4.1 Unitarity of the Cabibbo-Kobayashi-Maskawa Quark-Mixing Matrix

As was discussed in Sect. 2.3 already, the Cabibbo-Kobayashi-Maskawa matrix relates the quark eigenstates of the weak interaction with the quark mass eigenstates and, as such, is a unitary matrix. Testing unitarity can in principle be done for each of the rows and columns of the matrix. However, as the V_{ud} and V_{us} matrix elements are the ones that have till now been determined with the highest precision, the most precise test of unitarity to date is obtained from the first row of the CKM matrix, i.e.

$$\sum_i V_{ui}^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 \tag{60}$$

which should be equal to unity. The leading element, V_{ud}, depends only on the quarks in the first generation and can therefore be determined most precisely. The V_{us} matrix element is obtained from the so-called $e3$ branch of the K^+ decay (i.e. $K^+ \to \pi^0 e^+ \nu$) and from hyperon decays. The third matrix element in (60), V_{ub}, is obtained from B meson decays and is so small that it does not have any impact on the unitarity test at the present level of precision. If the CKM-matrix would turn out to be non-unitary this could point either to the existence of a fourth generation of fermions or to several types of new physics beyond the Standard Model, such as e.g. right-handed currents or non-V,A contributions to the weak interaction (e.g. [18]).

The V_{ud} element in the CKM matrix is best obtained from β-decay processes. It can be deduced from the $\mathcal{F}$t-values of superallowed $0^+ \rightarrow 0^+$ beta transitions, from neutron decay and from pion beta decay. Currently, the $\mathcal{F}$t-value of nine superallowed $0^+ \rightarrow 0^+$ pure Fermi transitions, ^{10}C, ^{14}O, ^{26}Al^m, ^{34}Cl, ^{38}K^m, ^{42}Sc, ^{46}V, ^{50}Mn and ^{54}Co, have been determined with a precision better than 2×10^{-3} [23,18].

The relation between the $\mathcal{F}$t-value and V_{ud} is for these pure Fermi transitions (see also (59))

$$\mathcal{F}t = ft\,(1 + \delta_R)\,(1 - \delta_C) = \frac{K}{2\,G_F^2\,V_{ud}^2\,(1 + \Delta_R^V)}\;. \tag{61}$$

Note that the right hand side of (61) contains only fundamental constants and parameters determined by the weak interaction, while the left hand side contains the experimentally determined quantities and calculated nuclear corrections. To determine the ft-value for a specific transition requires advanced spectroscopic methods since the half-life, the branching ratio as well as the transition energy, Q_{EC}, which is required to calculate f, all have to be known with good precision.

Further, the radiative corrections δ_R and Δ_R^V as well as the isospin correction δ_C must be calculated. The nucleus-dependent radiative correction δ_R can be split into a nuclear structure independent part, δ'_R, and a nuclear structure dependent part, δ_{NS}, i.e. $\delta_R = \delta'_R + \delta_{NS}$. The first is calculated from QED and is currently evaluated up to order $Z^2\alpha^3$ (e.g. [18] and references therein). For the nine above mentioned transitions the values of δ'_R range from 1.42% to 1.65% [18]. The nuclear structure dependent part, δ_{NS}, was calculated in the nuclear shell model with effective interactions and ranges from +0.03% to -0.36% [25]. For the nucleus-independent correction the currently adopted value is $\Delta_R^V = 0.0240(8)$ [18,24]. Several independent calculations were performed for the isospin symmetry-breaking correction δ_C (see [25] and references therein). Although the two leading calculations [25,27] exhibit a small difference, they are in reasonably good agreement, yielding values ranging from 0.2% to 0.6%. A detailed discussion of all these corrections can be found in [25].

According to the Conserved Vector Current (CVC) hypothesis [26] the $\mathcal{F}t$-value should be the same for all superallowed $0^+ \rightarrow 0^+$ transitions. The fit to a constant of the $\mathcal{F}t$-values obtained for the nine transitions yields $\mathcal{F}t = 3072.2(9)$ s [18] (Fig. 2), confirming the CVC hypothesis at the 3×10^{-4} precision level. Taking further into account an additional error related to a systematic difference between the two calculations of δ_c [25,27] one gets $\mathcal{F}t = 3072.2(20)$ s [18] which leads to $V_{ud} = 0.9740(5)$.

The matrix element V_{ud} can also be determined from the decay of the free neutron. The precision here has now come close to that of the $0^+ \rightarrow 0^+$

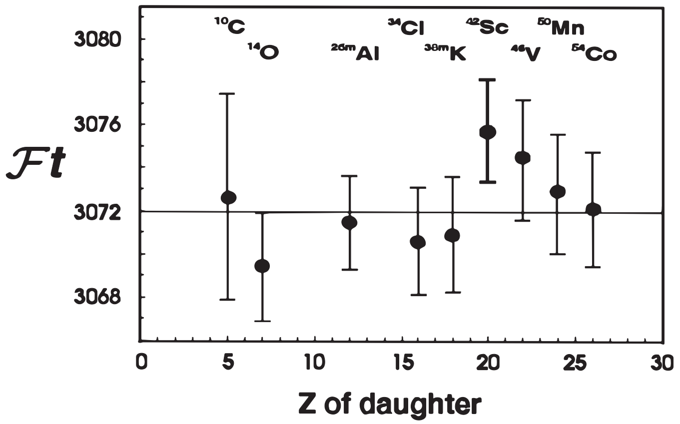

Fig. 2. $\mathcal{F}$t-values for the nine best studied $0^+ \to 0^+$ pure Fermi transitions. The line is the result from the best least-squares one-parameter fit. From [18].

transitions. The ft-value for the neutron is given by

$$f_n \, \tau_n \, (1 + \delta_R) \, (1 + 3\lambda^2) \; = \frac{K \, / \, \ln 2}{G_F^2 \, V_{ud}^2 (1 + \Delta_R^V)} \tag{62}$$

with τ_n the lifetime of the free neutron and $f_n(1+\delta_R) = 1.71489(2)$ the phase space factor [28,29]. The factor λ is the ratio of the effective vector and axial vector weak coupling constants $\lambda = G_A^{'}/G_V^{'}$, with $G_A^{'2} = G_A^2(1 + \Delta_R^A)$ and $G_V^{'2} = G_V^2(1 + \Delta_R^V)$. Here, $G_A = V_{ud} \, G_F \, g_A(q^2 \to 0)$, with g_A the axial vector form factor and $g_A(q^2 \to 0) \equiv C_A \approx -1.27$ the axial vector coupling constant. This factor λ enters because the decay of the neutron does not proceed through a pure Fermi transition but through a mixed Fermi/Gamow-Teller transition. Since the neutron is a single nucleon, no nuclear structure correction δ_{NS} or isospin symmetry-breaking correction δ_C have to be applied in this case. However, the factor λ has to be determined. This is usually obtained in measurements of the beta asymmetry parameter A (viz. the $\mathbf{I}.\mathbf{p_e}$ correlation; (39)). For neutron decay one has (assuming a pure $V - A$ interaction with maximal parity violation and time reversal invariance, neglecting recoil corrections and using $|M_F|$=1, $|M_{GT}| = \sqrt{3}$ for the neutron, cf. (50))

$$A_n = \frac{-2(\lambda + \lambda^2)}{1 + 3\lambda^2} \; . \tag{63}$$

Combining the world average value $\lambda = -1.2670(30)$ [17] with the recently published new, and till now also most precise value of $\lambda = -1.2739(19)$ [30], yields the new world average value $\lambda = -1.2703(24)$. Combining this with the world average value for the neutron lifetime, $\tau_n = 885.7(8)$ s [17], leads to $V_{ud} = 0.9736(17)$, in agreement with the value obtained from the superallowed transitions.

The value of V_{ud} can, finally, also be obtained from pion beta decay, $\pi^+ \rightarrow \pi^0\, e^+\, \nu_e$. As this is a $0^- \rightarrow 0^-$ pure vector transition, no separation of vector and axial-vector components is required. In addition, like neutron decay, it has the advantage that no nuclear structure-dependent corrections have to be applied. A major disadvantage, however, is that pion beta decay is a very weak branch, of the order of 10^{-8} only, leading to severe experimental difficulties. Combining the value for the lifetime $\tau_\pi = (2.6033 \pm 0.0005) \times 10^{-8}$ s given by the Particle Data Group [17], with the branching ratio $BR \simeq (1.044 \pm 0.007_{stat} \pm 0.009_{syst}) \times 10^{-8}$ that was obtained in a recent experiment at the Paul Scherrer Institute [31] yields $|V_{ud}| = 0.9771 \pm 0.0056$. Although this is in agreement with the values obtained from the superallowed $0^+ \rightarrow 0^+$ transitions and from neutron decay it is still much less precise, however.

Since the three above mentioned values for V_{ud} are in agreement with each other we will further use their weighted average, which turns out to be $V_{ud} = 0.9740(5)$. Combining this with the values recommended by the Particle Data Group [17] for the two other matrix elements in the first row, i.e. $V_{us} = 0.2196(26)$ and $V_{ub} = 0.0036(7)$ leads to

$$\sum_i V_{ui}^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9969(15) \tag{64}$$

which deviates 2.1σ from the Standard Model, a situation that exists for about two decades already.

Recently, however, a new determination of the K_{e3} branching ratio, which is at the basis of the Particle Data Group value for V_{us}, was carried out at Brookhaven National Laboratory. This new experiment yielded $V_{us} = 0.2272 \pm 0.0023_{stat} \pm 0.0007_{syst1} \pm 0.0018_{syst2}$ [32,33] which is about 2.5σ higher than the currently adopted value. In addition, V_{us} can also be extracted from hyperon β-decay data. It is interesting to note that the new value for V_{us} from K_{e3} decay is in good agreement with the value that was previously already obtained from the analysis of such hyperon decays, i.e. $V_{us} = 0.2258 \pm 0.0027$ [34]. However, this last value was not generally accepted as the analysis was believed to be subject to theoretical uncertainties due to first-order SU(3) symmetry-breaking effects in the axial-vector couplings. Recently Cabibbo *et al.* [35] have therefore re-analyzed the hyperon data using a technique that is not subject to these effects by focusing the analysis on the vector from factors. They obtained $V_{us} = 0.2250(27)$, again in good agreement with the new value from K_{e3} decay. The weighted average of these two values is $V_{us} = 0.2260(20)$. Because of the impact of V_{us} on the unitarity test it is important that the new value obtained from the K_{e3} branching ratio is confirmed by other experiments. Several of these are being prepared now [36,37].

If then the just mentioned weighted average value for V_{us} is used, perfect agreement with unitarity is obtained, i.e.

$$\sum_i V_{ui}^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9998(12)\ . \tag{65}$$

It thus appears that the long standing so-called unitarity problem has finally been solved. However, precise measurements of the $\mathcal{F}t$-values for superallowed $0^+ \rightarrow 0^+$ transitions continue to be of great importance, but now for nuclear structure reasons. Indeed, although our understanding of the different corrections has improved significantly over the years (for an overview see e.g. [25,18]) a systematic discrepancy between the two main sets of values for the isospin correction δ_c [25,27] still exists. Whereas this does not play a decisive role in the above test of unitarity of the CKM-matrix (since it amounts only to about 0.5% for the set of nine transitions that is used for this test), theoretical predictions for two additional sets of superallowed $0^+ \rightarrow 0^+$ transitions in the mass ranges 18 < A < 42 and 62 < A < 74 [38] yield values ranging from 0.8% up to 1.5%. Thus, the high precision of the average $\mathcal{F}$t-value for the set of nine well-studied transitions now provides an excellent basis to check our theoretical understanding of isospin symmetry in nuclei with unprecedented precision. More details on this can be found in another lecture in this book [4].

4.2 Right-Handed V-, A-currents

Whereas the violation of parity in the weak interaction was discovered more than 45 years ago [8], today its origin is still not understood.

So-called left-right symmetric extensions of the Standard Model explain the seemingly maximal violation of parity in the weak interaction by introducing a new gauge boson which couples to right-handed particles and which, by a spontaneous breaking of symmetry acquires a mass (m_2) that is larger than that of the observed W_1 boson (m_1) which couples mainly to left-handed particles [39]. The weak interaction eigenstates $W_{L(R)}$ are written as

$$W_L = \cos\zeta W_1 + \sin\zeta W_2 \tag{66}$$

$$W_R = -\sin\zeta W_1 + \cos\zeta W_2 \tag{67}$$

with W_1 and W_2 the mass eigenstates and ζ the mixing angle. The scale of the model is described by the parameter $\delta = (m_1/m_2)^2$. In so-called minimal left-right symmetric models δ and ζ are the only two parameters and the right-handed coupling constant g_R, the CKM quark-mixing matrix V_R, etc. are supposed to be identical to the left-handed ones. In more general left-right symmetric extensions of the Standard Model these may differ too.

Present constraints on right-handed currents from β-decay come from longitudinal positron polarization experiments [40–44], experiments in neutron decay [45–48], measurements of the longitudinal polarization of positrons emitted by polarized nuclei [49–52,59] and the $\mathcal{F}$t-values of the superallowed $0^+ \rightarrow 0^+$ transitions [18].

The average $\mathcal{F}$t-value for the superallowed $0^+ \rightarrow 0^+$ pure Fermi transitions provides a stringent constraint on the mixing angle ζ between the left- and right-handed gauge bosons. In a model where right-handed currents are assumed, one can write the $\mathcal{F}$t-value as

$$\mathcal{F}tV_{ud}^2(1-2\zeta) = \frac{K}{2G_F^2(1+\Delta_R^V)} \ . \tag{68}$$

Using the previously cited value $\mathcal{F}\mathrm{t} = 3072.2(20)$ s, the above mentioned new value for $V_{us} = 0.2260(20)$, $V_{ub} = 0.0036(7)$ and requiring that V_{ud}^2 satisfies unitarity, one finds $\zeta = 0.0001(7)$. The mixing angle for the left- and right-handed gauge bosons is thus clearly limited to the milliradian region: $-0.0011 \leq \zeta \leq 0.0013$ (90 % C.L.). This is currently the strongest limit on ζ.

Stringent limits on both δ and ζ were obtained from measurements of the longitudinal polarization of positrons from nuclear β-decays and from measurements of the β- and neutrino asymmetry parameters A, respectively B in the decay of polarized neutrons (a detailed discussion can be found in [1, 45]). In the first case relative measurements were performed comparing pure Fermi and pure Gamow-Teller transitions [41–44]:

$$P_L^F/P_L^{GT} \simeq 1 + 8\delta\zeta \ . \tag{69}$$

The weighted average result of all these experiments yielded -4.0 $< \delta\zeta \times 10^4 <$ 7.0 (90% C.L.) [43]. However, as this method yields a limit for the product $\delta\zeta$, no limits on the mass related parameter δ are obtained for the small values of ζ that result from the average $\mathcal{F}$t-value of the $0^+ \to 0^+$ transitions.

A detailed discussion of measurements determining the A- and B-parameters in neutron decay can be found in [46,53]. Whereas the β-asymmetry parameter A in neutron decay yields limits for δ and ζ comparable to those from the positron polarization experiments (e.g. [46]), a measurement of the neutrino-asymmetry B yields an ellipse in the δ versus ζ plane, thus providing an upper limit on δ (corresponding to a lower limit on the mass of a possible W_R boson with right-handed couplings). Recently, two precise measurements of the B-parameter were performed [47,48]. Both experiments used the same set-up (Fig. 3).

The momentum and angle of escape of the undetected antineutrino were deduced from the coincident detection of the decay electron and recoil proton, and the subsequent measurement of their momenta. The electron detector was a photomultiplier with a plastic scintillator. The protons were accelerated and focused by an electric field onto a micro channel plate detector. This allowed to determine the time of flight for each proton to an accuracy of 10 ns, from which the momentum was then deduced. The weighted averaged result of the two measurements, B=0.9821(40) yields a lower limit of 280 GeV/c^2 (90 % C.L.) for the mass of a W_R boson.

The most stringent limits on the mass of a possible W_R boson in nuclear β-decay were obtained from measurements of the longitudinal polarization of positrons emitted by polarized nuclei (so-called polarization-asymmetry correlation). In contrast to the above mentioned longitudinal polarization

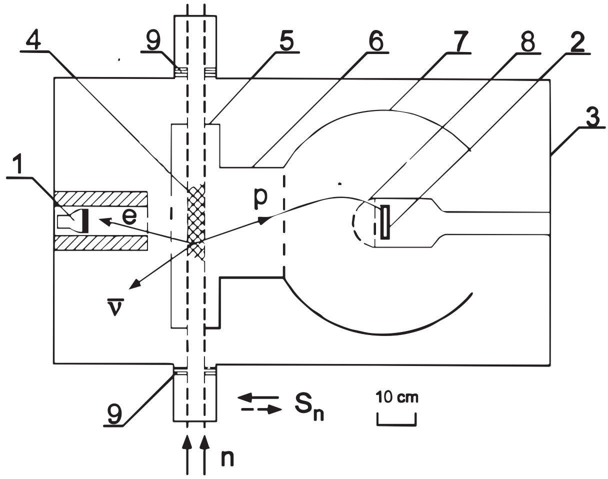

Fig. 3. Experimental apparatus used for measuring the B-parameter in neutron decay. (1) Electron detector, (2) proton detector, (3) vacuum chamber, (4) decay region, (5) cylindrical electrode, (6) TOF chamber, (7) spherical electrode, (8) spherical grid, and (9) LiF diaphragm. From [47].

measurements with unpolarized nuclei that determine the product $\delta\zeta$, this observable determines the parameter $(\delta+\zeta)^2$ [54]. Measurements of this correlation were carried out using the method of time-resolved spectroscopy of positronium hyperfine states to determine the longitudinal polarization of the decay positrons [55,44]. The experimental quantity that was addressed was either the ratio

$$P^-/P^+ = R_0 \left[1 - \frac{8\beta^2 \vec{\beta} \cdot \vec{I}A}{\beta^4 - \left(\vec{\beta} \cdot \vec{I}A\right)^2} (\delta+\zeta)^2 \right] \tag{70}$$

of positron polarizations P^- and P^+ for positrons emitted in two opposite directions with respect to the polarized nuclear spin direction and with

$$R_0 = \left[\frac{\beta^2 - \vec{\beta} \cdot \vec{I}A}{\beta^2 + \vec{\beta} \cdot \vec{I}A} \right] \left[\frac{1 + \vec{\beta} \cdot \vec{I}A}{1 - \vec{\beta} \cdot \vec{I}A} \right] , \tag{71}$$

$\beta = v/c$, $\vec{\beta}.\vec{I}A$ the experimental beta asymmetry, I the nuclear polarization and A the β-asymmetry parameter, or alternatively the ratio

$$P^-/P^0 = R_0 \left[1 - \frac{4\vec{\beta} \cdot \vec{I}A}{\beta^2 - \left(\vec{\beta} \cdot \vec{I}A\right)} (\delta+\zeta)^2 \right] \tag{72}$$

of the polarization of positrons emitted opposite to the polarized nuclear spin direction, P^-, and of positrons emitted by unpolarized nuclei, P^0, with

$$R_0 = \frac{\beta^2 - \vec{\beta} \cdot \vec{I}A}{\beta^2(1 - \vec{\beta} \cdot \vec{I}A} \ . \tag{73}$$

As $\beta = v/c$ is in most cases close to unity it follows from (70) and (72) that interesting candidates for this type of experiments are nuclei for which a large degree of nuclear polarization can be obtained and which decay via a pure Gamow-Teller transition of the type $I \rightarrow I - 1$, with a maximal asymmetry parameter $A = 1$ (see (43) and (59)). Further, due to the relative character of this type of experiments a number of systematic effects are reduced significantly or even eliminated.

The first measurement [49], at the LISOL isotope separator coupled to the CYCLONE cyclotron in Louvain-la-Neuve, used the isotope ^{107}In ($t_{1/2} = 32.4$ m) (Fig. 4), which was polarized with the method of low temperature nuclear orientation [57,56]. This method combines temperatures in the millikelvin region obtained in a ^{3}He-^{4}He dilution refrigerator, with the large magnetic hyperfine fields, ranging from a few Tesla to several hundreds of Tesla, which impurity nuclei feel in a ferromagnetic host lattice. The second measurement, carried out at the Paul Scherrer Institute (PSI), used ^{12}N ($t_{1/2} = 11.0$ ms) that was produced and polarized in the $^{12}C(\overrightarrow{p}, n_0)^{12}\overrightarrow{N}$ polarization transfer reaction initiated by a 70% polarized proton beam [58, 50]. With each isotope two measurements were performed, the second one always after considerable improvements of the experimental set-up. For ^{107}In an experimental β-asymmetry $\vec{\beta} \cdot \vec{I}A \approx 0.50$ was obtained, corresponding to a nuclear polarization of $\sim 65\%$. The final result obtained with this isotope was $(\delta + \zeta)^2 = 0.0021(17)$ [59,51]. In the second measurement with ^{12}N an experimental beta asymmetry $\vec{\beta} \cdot \vec{I}A \approx 0.13$ was obtained, corresponding to a nuclear polarization of $\sim 15\%$. This yielded $(\delta + \zeta)^2 = -0.0004(32)$ [52]. If interpreted in the manifest left-right symmetric model, both results correspond to a 90% lower limit for the mass of a W_R vector boson of 303 GeV/c^2. These are the most sensitive tests of parity violation in nuclear beta decay to date. The lower limit from the combined result of both experiments is 320 GeV/c^2 (90% C.L.).

An overview of constraints on the parameters δ and ζ from different experiments in nuclear and neutron β-decay is given in Fig. 5.

Although the limits for the mass of a W_R boson with right-handed couplings from β-decay are weaker than the lower limit of 720 GeV/c^2 for a heavy W' boson obtained from $p\overline{p}$ collisions at Fermilab [60], results from β-decay and from collider experiments are complementary when interpreted in more general left-right symmetric extensions of the Standard Model such as e.g. models which allow for different gauge coupling constants in the left- and right-handed sectors or for different CKM matrices. This is discussed and illustrated in [52,61,62].

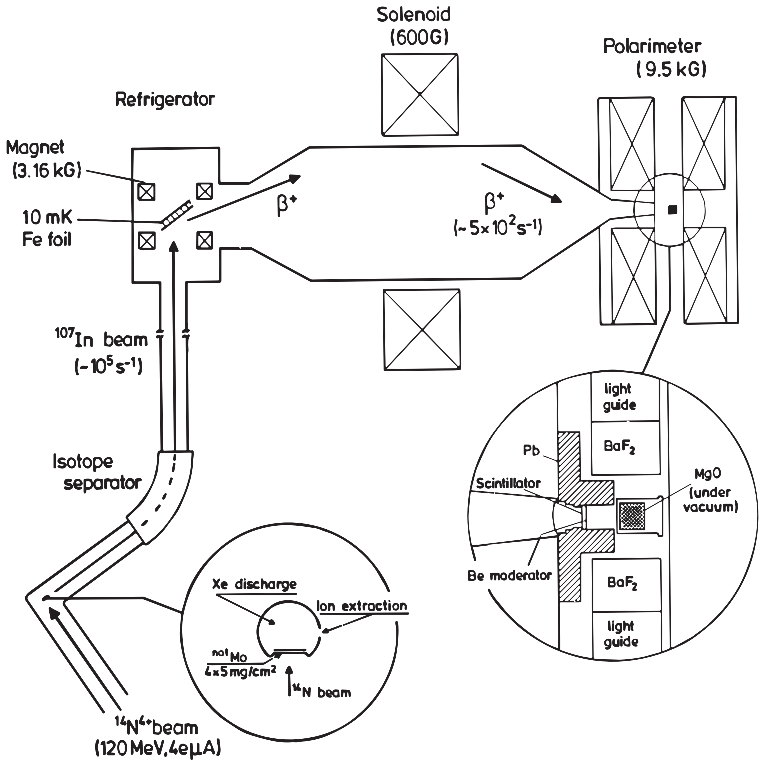

Fig. 4. Experimental set-up to measure the longitudinal polarization of positrons emitted in the decay of polarized ^{107}In nuclei. The radioactive ions delivered by the isotope separator are implanted and oriented in a iron foil at a temperature of 10 mK inside a dilution refrigerator. The positrons emitted in the decay of the polarized nuclei are energy-selected with a spectrometer and then slowed down and stopped in a MgO pellet. A plastic scintillator and two BaF_2 scintillators observe the decay of the positronium that is formed when the positrons come to rest in the MgO. The longitudinal polarization of the positrons is obtained from this positronium decay spectrum. From [51].

4.3 Exotic Interactions

Apart from the observed V- and A-type interactions the general β-decay hamiltonian also allows for the existence of scalar (S) and tensor (T) type weak interactions. Scalar and tensor type interactions in the $d \rightarrow ue^- \overline{\nu}_e$ decay can arise in different types of extensions of the Standard Model, such as e.g. models with leptoquarks and supersymmetric models (see e.g. [62]).

Constraints on S- and T-type weak coupling constants in β-decay are usually obtained either from the Fierz interference term b' or from the $\beta\nu$-correlation coefficient a. The Fierz interference term b' (41, 47, 48) depends linearly on the coupling constants. In the Standard Model with only V- and

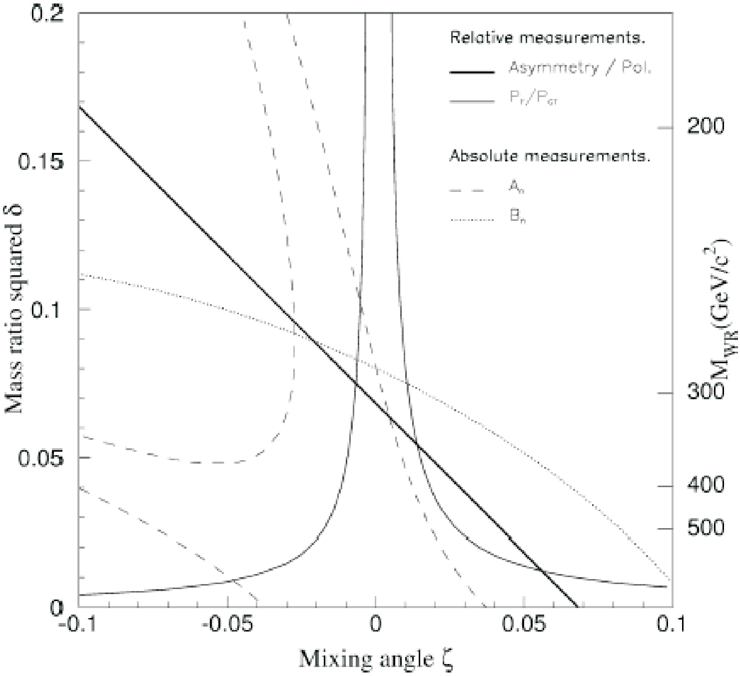

Fig. 5. Constraints (90% C.L.) for the right-handed current parameters δ and ζ from different nuclear β-decay experiments: asymmetry/polarization correlation (thick line) [59,51,52], P_F/P_{GT} polarization ratio (thin line) [44] (and references therein), β-asymmetry parameter A_n in neutron decay (dashed line) [17], neutrino-asymmetry parameter B_n in neutron decay (dotted line) [48]. From [52].

A-couplings $b' = 0$. A measurement of b' then yields a narrow band as constraints in the C_i versus $C_i^{'}$ (i= S or T) parameter plane. However, this band extends to infinity while, in addition, b' is identically zero for scalar and tensor interactions if $C_i = -C_i^{'}$ (cf. (47 48)).

The $\beta\nu$-correlation coefficient a (viz. the $\mathbf{p_e}.\mathbf{p}_\nu$ correlation; (39, 45 and 46)) depends quadratically on the exotic coupling constants. A higher experimental precision is thus needed in this case in order to get the same absolute constraints on the coupling constants as in measurements of the Fierz interference term. However, a measurement of a constrains a closed region (circle) in the parameter plane and is independent on the helicity properties of the interactions. It is because of these two properties that the $\beta\nu$-correlation is usually preferred for scalar and tensor current searches. Note that for a Fermi transition one has $a_F = +1$ for a pure V-interaction and $a_F = -1$ for a pure S-interaction, while for a Gamow-Teller transition $a_{GT} = -1/3$ for a pure A-interaction and $a_{GT} = +1/3$ for a pure T-interaction.

Strong limits on scalar and tensor couplings were recently obtained from the Fierz interference term extracted from the $\mathcal{F}t$-value of the superallowed $0^+ \rightarrow 0^+$ transitions and from the so-called polarization asymmetry correlation. Assuming the existence of a scalar component in the weak interaction, the $\mathcal{F}t$-value for the $0^+ \rightarrow 0^+$ transitions is written as

$$\mathcal{F}t = ft(1+\delta_R)(1-\delta_C) = \frac{K}{2G_F^2 V_{ud}^2(1+\Delta_R^V)} \frac{1}{(1+\langle b'_F \rangle)} \tag{74}$$

with b'_F the Fierz interference term for a pure Fermi transition, as defined in (47), and $\langle\ \rangle$ denotes an average over the energy region observed. It follows that $(C_S + C_S^{'})/C_V = -0.0027(29)$, corresponding to $-0.0075 < (C_S + C_S^{'})/C_V < 0.0021$ (90% C.L.) [18]. Strong limits for tensor couplings were recently obtained from the Fierz interference term in the so-called polarization asymmetry correlation experiment with ^{107}In that was discussed in the previous section, yielding $-0.034 < (C_T + C_T^{'})/C_A < 0.005$ (90% C.L.) [63,59]. Note, however, that these two results do not contain any information if for these exotic interactions $C_i = -C_i^{\prime}$.

A combined analysis of relevant experimental data in nuclear β-decay (including neutron decay data) yielded the following limits for scalar and tensor coupling constants [1] (95% C.L.)

$$|C_S^{(')}/C_V| < 0.08 \tag{75}$$

$$|C_T^{(')}/C_V| < 0.08\ . \tag{76}$$

Thus, 40 years after it was established that the weak interaction is dominated by V- and A-currents [22], scalar and tensor currents are ruled out only to the level of about 8% of the vector type interaction. The present constraints therefore still allow to accommodate sizable contributions of scalar and tensor type interactions without affecting our conclusions on the phenomenology of semi-leptonic weak processes. We will now discuss some of the ongoing experiments in this respect.

Since neutrinos are very hard to detect, the $\beta\nu$-correlation in semi-leptonic processes is usually investigated by observing the β-particle and/or the recoiling nucleus, taking into account the kinematics of the decay.

Recently a precise measurement of the $\beta\nu$-correlation was performed by determining the kinematic broadening of β-delayed protons in the $0^+ \rightarrow 0^+$ Fermi decay of ^{32}Ar [64,65] (Fig. 6), resulting in $\widetilde{a} = 0.9989 \pm 0.0052_{stat} \pm 0.0039_{syst}$. For this, the ^{32}Ar nuclei were implanted into a $22.7\mu g/cm^2$ carbon foil inclined at 45° to the beam axis. The protons were detected with two thin *pin* diode Si detectors placed close to the beam axis. A 3.5 T magnetic field prevented the β-particles from reaching the proton detectors, thus avoiding possible uncertainties from β-summing effects, but had little effect on the protons.

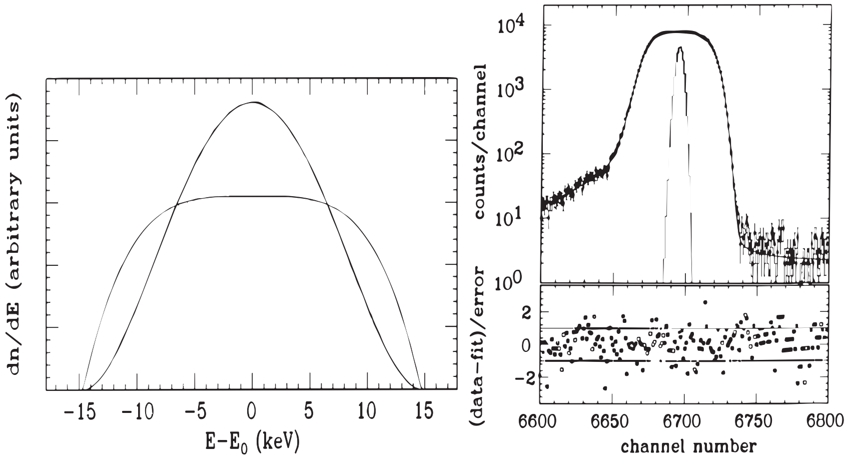

Fig. 6. Left: Intrinsic shapes of the delayed proton group from ^{32}Ar $0^+ \to 0^+$ decay for $a = +1, b' = 0$ (pure V-interaction, "flat" curve) and $a = -1, b' = 0$ (pure S-interaction, "Gaussian"-like curve); Right: Fit (top) and residuals (bottom) of the $0^+ \to 0^+$ proton peak (0.500 keV/channel). The narrow pulser peak shows the electronic resolution. From [64,65].

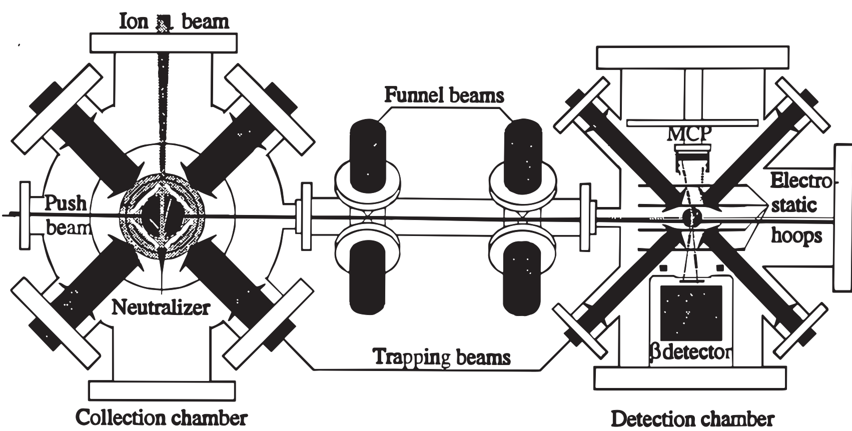

Fig. 7. Top view of the TRIUMF two-MOT apparatus. From [69].

The advent of atom and ion traps in nuclear physics (e.g. [66–68]) which allow one to detect the β-particles and recoil ions resulting from β-decay with minimal disturbance from the host material or from scattering, has triggered a new series of measurements of the $\beta\nu$-correlation and the β-asymmetry parameter A, aiming at the study of exotic weak interactions.

The first successful application of an atom trap in a correlation measurement in nuclear β-decay was the TRINAT experiment at TRIUMF [69]. This experiment (Fig. 7) uses two Magneto Optical Traps (MOT) [70] and is set up on-line at the ISAC isotope separator. The possible presence of a scalar type weak interaction is probed by investigating the $\beta\nu$-correlation in the pure Fermi decay of ^{38m}K. The ^{38m}K ions are implanted in a Zr foil that is periodically heated in order to release the atoms which are then trapped in a first MOT. To escape the large background from un-trapped atoms, the trapped atoms are at regular intervals transferred to a second MOT by a laser push beam and 2-d magneto-optical funnels. The β-particle telescope detectors and a Z-stack of three microchannel plates to detect the recoil ions are installed in this second MOT. The $\beta\nu$-correlation coefficient a is obtained from fitting the recoil time-of-flight spectra. The preliminary result is $\widetilde{a} = 0.9978 \pm 0.0030_{stat} \pm 0.0045_{syst}$ [71,72], in agreement with the Standard Model value of unity.

At Berkeley a MOT was recently used to study the $\beta\nu$-correlation in the mixed decay of the mirror nucleus ^{21}Na [73]. As this transition is mainly (67%) of Fermi character, this experiment is also predominantly sensitive to scalar currents. The $\beta\nu$-correlation coefficient a was obtained from the time-of-flight spectrum of the recoiling ^{21}Ne ions. The result, $a = 0.5243(92)$, differs by about 3 standard deviations from the value of 0.558(3) that is calculated for this transition in the Standard Model using the experimental ft-value [74]. A possible explanation for this discrepancy could be that the branching ratio that goes in this ft-value is wrong. Several groups are now planning to remeasure this branching ratio.

Experiments to measure the $\beta\nu$-correlation using electromagnetic traps are presently being set up as well, one at GANIL-Caen [75,76], the other at ISOLDE [77,78]. In the first set-up a low energy ^{6}He beam produced at the SPIRAL facility at GANIL will be slowed down by a quadrupole RFQ [79] and subsequently injected into a Paul trap. This trap has a very open structure to avoid scattering of the decay products on the trap electrodes. The quadrupole trapping field is generated by four ring electrodes. The $\beta\nu$-correlation coefficient will be obtained from coincident detection of the β-particles and the recoil nuclei [76]. This experiment is sensitive to tensor currents and aims at improving the old experiment of Johnson et al. [80] who determined a_{GT} in the decay of ^{6}He with a 1% precision.

In the second set-up [77,78] (Fig. 8) a pulsed ^{35}Ar beam coming from the REXTRAP Penning trap at ISOLDE will be decelerated in a pulsed drift tube and catched in a first Penning trap placed in a 9 T magnetic field. The ions are cooled in there and then transferred to a second Penning trap. Recoil ions from decays in this second trap are guided into a spectrometer, where their energy is probed in a low field region (0.1 T) using the retardation principle [81]. Only the recoils having an energy large enough to overcome the retardation potential will reach the micro channel plate detector. The $\beta\nu$-correlation coefficient will be obtained by fitting the measured shape of the recoil ion energy spectrum. Since the Gamow-Teller component in the mirror β-decay of ^{35}Ar is small ($\simeq$ 7%), this experiment will mainly probe the existence of scalar weak currents. A precision of well below 1% is aimed at.

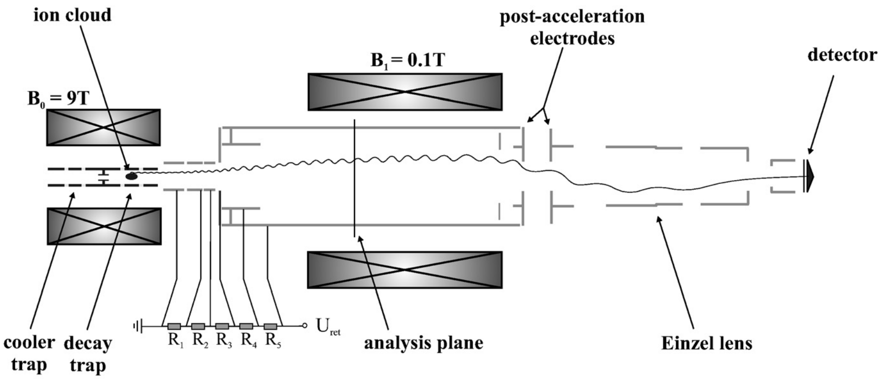

Fig. 8. Spectrometer section of the WITCH set-up. The cooler and decay Penning traps are located in a region with $B = 9$ T. The retardation electrodes are in the region between the end of the decay trap and the end of the low-field magnet. The retardation potential reaches its maximum ("analysis plane") in the homogeneous field region of the 0.1 T magnet. Then follow a screening electrode and the electrodes for post-acceleration. Finally, the Einzel lens focuses the ions that make it over the retardation potential on to the MCP detector. From [77].

Finally, at the Los Alamos National Laboratory a MOT-based experiment is being carried out [82,83] to determine the beta-asymmetry parameter for the pure Gamow-Teller decay of ^{82}Rb, searching for a tensor component in the weak interaction. ^{82}Rb ions from an isotope separator are transformed into atoms and trapped into a first MOT in a way similar to the method used for ^{38m}K at TRIUMF. The trapped atoms are then transferred with a laser push beam to the second MOT where they are re-trapped and polarized by optical pumping. Applying a rotating bias field with which the nuclear spin vector is aligned then allows to measure the β-particle emission asymmetry parameter A as a continuous function of the β-energy and the angle between the β-particle and the nuclear spin vector, using a single β-detector. A precision of well below 1% is again aimed at.

4.4 Time Reversal Violation

At present there are two unambiguous pieces of evidence for time reversal violation (T-violation) and CP-violation, *i.e.* the decay of neutral kaons [13] and B-mesons [86,85] and the excess of baryonic matter over antimatter in the Universe [84]. However, whereas the first can be incorporated in the Standard Model via the quark mixing mechanism, the excess of baryons over antibaryons cannot. Further, the Standard Model predictions of T-violation originating from the quark mixing scheme (*i.e.* the phase δ_{13} in the CKM matrix (10)), are by 7 to 10 orders of magnitude lower than the experimental accuracies presently available for systems built up of u and d quarks. Thus, any sign for the presence of T-violation in nuclear β-decay observables or processes would be a signature of a non-Standard Model source of T-violation. New T-violating phenomena may be generated by several mechanisms like the exchange of multiplets of Higgs bosons, leptoquarks, right-handed bosons, etc. Although these exotic particles do not contribute to the V-A form of the weak interaction, they may generate scalar or tensor variants of the weak interaction or a phase different from 0 or π between the vector and axial-vector coupling constants. It is a general assumption that time reversal phenomena may originate from a tiny admixture of such new exotic interaction terms. Weak decays provide a favorable testing ground in a search for such new feeble forces [87,88].

Direct searches for time reversal violation, and consequently CP-violation, via correlation experiments in β-decay require the measurement of terms including an odd number of spin and/or momentum vectors. The D-triple correlation ($\mathbf{I}.\mathbf{p_e} \times \mathbf{p}_\nu$, (39) [21]) is sensitive to parity(P)-even, T-odd interactions with vector and axial-vector currents and requires the use of mixed Fermi/Gamow-Teller transitions. For the neutron the Standard Model prediction for the magnitude of this correlation coefficient, based on the observed CP-violation, is $D < 10^{-12}$. Any value above the final state effect level, which is typically at the 10^{-5} level, would thus indicate new physics.

Another time reversed violation sensitive correlation in β-decay is the R-triple correlation ($\boldsymbol{\sigma} \cdot \mathbf{I} \times \mathbf{p_e}$, (39) [21]) which probes the transverse polarization of the emitted β-particles in a plane perpendicular to the polarized nuclear spin axis. It is sensitive to P-odd components of T-violating scalar and tensor interactions.

Measurements of these D- and R-triple correlations are very difficult as they require the use of polarized nuclei/neutrons and at the same time the determination of either the neutrino momentum via detection of the recoil ion (D-correlation), or of the transverse polarization of the β-particle (R-correlation). No indication for a time reversal violation has been found as yet.

The most precise limit on a T-violating angular correlation in a weak decay process comes from the combined result of two D-triple correlation measurements that were carried out at Princeton with the mirror nucleus ^{19}Ne, yielding $D = 0.0001(6)$ [89]. Recently, two new and very precise measurements of the D-triple correlation have been performed in neutron decay. At the Institit Laue Langevin at Grenoble the TRINE experiment has yielded $D_n = [-3.1 \pm 6.2(stat) \pm 4.7(syst) \pm 4.7(syststat)] \times 10^{-4}$ [90]. The result of the *emi*T experiment at the National Institute for Standards in Technology at Gaithersburg is $D_n = [-0.6 \pm 1.2(stat) \pm 0.5(syst)] \times 10^{-3}$ [91]. Both setups are currently being improved to reach even higher precision in a second phase.

The highest-precision measurement of the R-triple correlation in nuclear β-decay was performed at the Paul Scherrer Institute, using the pure Gamow-Teller decay of ^{8}Li [92,93]. Polarized ^{8}Li nuclei were produced by a vector-

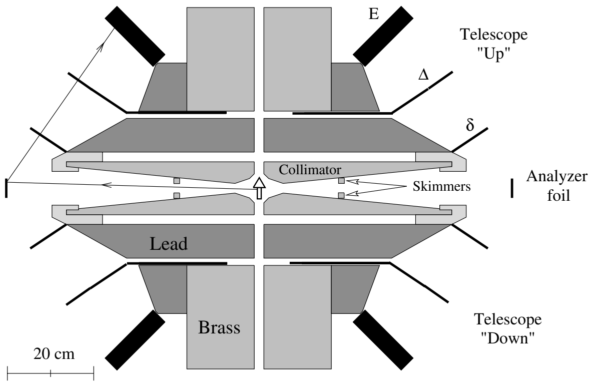

Fig. 9. Vertical cross section through the Mott polarimeter used in the ^{8}Li R-correlation experiment. The direction of incidence of the polarized deuteron beam is perpendicular to the figure. The central arrow indicates the direction of the ^{8}Li spin in the target. A trajectory of an electron scattered on the lead analyzer foil is also shown. From [93].

polarized deuteron beam on an enriched ^{7}Li metal foil target. This was cooled to liquid helium in order to achieve a long polarization relaxation time, i.e. $t \geq 20$ s, an order of magnitude longer than the mean decay time for ^{8}Li ($\tau =$ 1.21 s). The transverse polarization of the ^{8}Li decay electrons was deduced from the measured asymmetry in Mott scattering at backward angles using a lead foil as analyzer. To obtain a large solid angle the detectors were arranged in a cylindrical geometry around the ^{8}Li polarization axis. In fact, the set-up (Fig. 9) was made of four separate azimuthal segments, each containing an upper and a lower telescope, thus providing four independent measurements of the electron polarization. Each telescope consisted of two thin transmission scintillators followed by a thick stopping scintillator. Much attention was paid to the passive shielding of the detectors against background radiation produced in the target area. The weighted average result of six runs, corrected for the effects of the final state interaction (FSI) which can mimic a genuine time reversal violation in the R-correlation and which was calculated to be $R_{FSI} = 0.7(1) \times 10^{-3}$, is R(^{8}Li) = 0.0009(22) [93]. This is by one to two orders of magnitude more precise than similar triple correlation experiments in the decays of polarized Λ^0 particles and polarized muons [92] and corresponds to very stringent bounds for T-violating charge changing tensor couplings, i.e. $-0.008 < Im(C_T + C_T^{'})/C_A < 0.014$ (90% C.L.).

5 Summary and Outlook

Nuclear β-decay has in the past played a key role in the determination of some of the basic properties of the weak interaction (viz. the discovery of parity violation [8] and the determination of the V-A structure of the interaction [22]). Later, dedicated experiments in nuclear and neutron β-decay have yielded very precise measurements of a number of observables (ft-values, correlation coefficients, ...) which, when compared to their Standard Model prediction, provide sensitive tests of different types of physics not included in this model. Since the energy available in nuclear β-decay is typically only a few MeV the gauge particles related to possible new weak interaction types cannot be produced directly but their possible existence can be revealed by searching for the tiny modifications they induce in the values of experimental observables. The information provided by such experiments is in general complementary to that obtained in experiments in muon decay or at colliders because measurements in the three sectors of the weak interaction usually constrain different combinations of the relevant new physics parameters. However, the high precision that is needed in weak interaction studies in nuclear β-decay constitutes a true challenge. The development of high-precision spectroscopic techniques, the availability of pure and intense beams of a wide range of radioactive isotopes at isotope separators and improved beam intensities and beam polarizations at neutron facilities have significantly contributed to the high-precision that was reached in the determination of the V_{ud} CKM matrix element and has triggered new and more precise tests of parity violation and new searches for scalar and tensor components in the weak interaction, too. Further, also the advent of atom and ion traps has significantly extended the experimental possibilities since these provide well localized samples free of any host material. Apart from a significant reduction of scattering effects this now also allows for new precision experiments in which the recoil ion resulting from β-decay is to be observed, e.g. β-ν-correlation measurements. All these developments and the new experiments that are currently being prepared and planned assure that also in future nuclear and neutron β-decay will continue to play a significant role in the study of weak interaction properties.

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