Eur. Phys. J. A **15**, 217–221 (2002)
DOI 10.1140/epja/i2002-10040-x

THE EUROPEAN
PHYSICAL JOURNAL A

Low-energy weak-interaction studies

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Received: 21 March 2002 /

Abstract. An overview is given of the present status of low-energy tests of the Standard Model in nuclear beta-decay and neutron decay, covering the unitarity problem, searches for right-handed currents, scalar- and tensor-type currents, tests of time-reversal violation, as well as experiments to set the neutrino mass scale. In view of the large amount of ongoing and planned experiments in this sector, many new results can be expected in the coming decade.

PACS. 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries – 12.15.Hh Determination of Kobayashi-Maskawa matrix elements – 23.40.Bw Weak-interaction and lepton (including neutrino) aspects

1 Introduction

The successful unification of the weak and the electromagnetic interactions, about thirty years ago, represented a major breakthrough in our understanding of the weak interaction. Nevertheless, the present Standard Model (SM) for the particles and their interactions is generally believed not to be the ultimate description of Nature as it contains too many parameters that have to be determined by experiment, while also features such as parity violation and CP-violation, for example, are not explained by the model itself. Over the years, many experiments, ranging from the low-energy scale of nuclear beta-decay to the very highest energies at colliders, have put the SM to the test, searching for possible deviations which could point out in which direction the model has to be extended. All experiments found the model to be working well, within experimental error bars, and it was only recently that a first convincing sign for new physics, not included in the SM, was found, in neutrino physics [1]. As it is to be expected that the SM is incomplete in other sectors as well, continued searches for new physics, covering the full energy scale, are of utmost importance.

Several important properties of the weak interaction, such as parity violation [2] and the well-known V-A structure of the interaction [3] were discovered in nuclear beta-decay. Also today, precision measurements in nuclear and neutron beta-decay continue to be an efficient tool to search for new physics beyond the standard electroweak model. In this approach precision measurements are carried out to determine the parameters related to the structure of the weak lepton-quark current or to search for tiny effects that would be induced by the exchange of new massive particles. Such experiments can explore energy regions and features that at present cannot be probed in muon decay and at high-energy colliders (*e.g.*, at CERN and at Fermilab) where one searches for the direct production of new massive particles. Both approaches are thus largely complementary in the parameter regions that can be probed. Also, the abundance and variety of available quantum states of the nucleus allow one to perform selective experiments of high precision, with the impact of nuclear-structure–induced uncertainties being negligible in well-selected cases. This is even more so in the decay of the neutron, as this consists of only one single nucleon.

2 Formalism

For allowed beta-decays the most general Lorentz invariant Hamiltonian for a four-fermion interaction allows for the existence of scalar (S), vector (V), axial-vector (A), tensor (T) and pseudoscalar (P) type contributions and makes no *a priori* assumptions about the parity and time-reversal properties of these [4]:

$$H_\beta = \frac{G_F}{\sqrt{2}} V_{ud} \sum_i (\bar{\psi}_p O_i \psi_n)[\bar{\psi}_e O_i (C_i + C_i' \gamma_5)\psi_\nu] + \text{h.c.} \quad (1)$$

Here $i = S, V, T, A, P$ and O_i are the respective operators, while C_i and C_i' are, respectively, the parity-conserving and parity-violating coupling constants for the different interactions. These coupling constants might in general be complex, and invariance under time reversal requires all couplings be relatively real. The SM corresponds

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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 $O_P = \gamma_5$ couples large to small components of the nuclear wave functions and thus the hadronic matrix element with O_P in the above Hamiltonian is very small.

Which of the other interactions actually do occur in Nature, as well as their properties with respect to the P- and T-operations, can be investigated by measuring ft-values for well-chosen transitions or by measuring different types of correlations between the spin and momentum vectors of the particles involved in beta-decay (*i.e.* the spin $\mathbf{J}$ of the nucleus, the spin σ and momentum $\mathbf{p}$ of the beta-particle and the momentum $\mathbf{q}$ of the (anti)neutrino) [5]. Such experiments yield the so-called correlation coefficients that depend only on the nuclear matrix elements for the observed beta transition and on the weak-interaction coupling constants. If a pure Fermi or pure Gamow-Teller transition is used, the dependence on the nuclear matrix elements cancels.

As is well known, all experiments 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. In the coming decade a new generation of ongoing and planned experiments in nuclear beta-decay and in neutron decay will enhance our knowledge about the possible presence of right-handed currents, scalar or tensor currents and time-reversal violation, determine the V_{ud} Cabibbo-Kobayashi-Maskawa (CKM) matrix element with better precision (to test unitarity), and set the neutrino mass scale. In addition, these experiments will, at the same time, provide constraints on a wide range of extensions of the Standard Model, such as models involving leptoquarks.

3 Unitarity of the CKM matrix

Currently the ft-values of nine superallowed $0^+ \to 0^+$ transitions, *i.e.* ^{10}C, ^{14}O, ^{26}Al$^{\rm m}$, ^{34}Cl, ^{38}K$^{\rm m}$, ^{42}Sc, ^{46}V, ^{50}Mn and ^{34}Co, have been measured to a precision better than 2×10^{-3} [6,7]. Whereas the analysis of the presently available data set confirms the CVC hypothesis at the 3×10^{-4} precision level, the unitarity test, based on the extracted value of V_{ud}, points to a 2.2 σ deviation from the Standard Model [6,7]. The matrix element V_{ud} can also be determined from the decay of the free neutron and the precision here has now come close to that of the $0^+ \to 0^+$ transitions. A recent analysis of the world data on neutron decay yielded a value of V_{ud} in agreement with unitarity [7]. However, if one considers only the most recent measurements in neutron decay which lead to V_{ud} (*i.e.* a measurement of the correlation coefficient A ($\mathbf{J} \cdot \mathbf{p}$ correlation) [8] and of the ratio $(A - B)/(A + B)$ (with B the coefficient for the $\mathbf{J} \cdot \mathbf{q}$ correlation) [9]), a value which deviates about 2.5 σ from the Standard Model is obtained, the deviation being in the same direction as in the case of the $0^+ \to 0^+$ transitions. If this deviation is genuine, it could be due either to new physics or to a non-perfect understanding of one or more of the different corrections that are involved [6,7].

From the above it is clear that new precise experiments in both nuclear and neutron beta-decay are needed. In nuclear beta-decay, improved detection techniques at isotope separators and at recoil separators, Penning traps for precision mass measurements and improved production techniques for exotic isotopes, allow for new precision measurements on the $0^+ \to 0^+$ transitions with $A \leq 54$, as well as, more importantly, measurements on several new $0^+ \to 0^+$ transitions in the decay of isotopes with $A > 54$, *i.e.* ^{62}Ga, ^{66}As, ^{74}Rb, (see refs. [6,10]). In neutron decay several Russian, Western European and U.S. groups are preparing/planning new measurements of the neutron half-life $\tau_{\rm n}$, the β-ν correlation coefficient a ($\mathbf{p} \cdot \mathbf{q}$ correlation) and the β-asymmetry parameter A. At the same time, the other matrix element which is important for the unitarity test, *i.e.* V_{ub}, is currently being addressed again in high-energy physics, both experimentally and theoretically [11].

4 Scalar and tensor currents

Constraints on these types of exotic weak couplings can be obtained both from the Fierz interference term b and from the β-ν correlation coefficient a [5]. The first depends linearly on the coupling constants but is trivially zero if the exotic couplings are purely left-handed. The second depends only quadratically on the coupling constants so that a higher experimental precision is needed, but is independent of the helicity properties of the interactions. Because of this last property, the β-ν correlation is usually preferred for scalar and tensor current searches. With the advent of ion and atom traps in nuclear physics, which allow detection of beta-particles and recoil ions without or with minimal disturbance from scattering and slowing-down effects, this correlation has gained even more interest in recent years.

The present constraints (95% C.L.) on time-reversal invariant (TRI) scalar- and tensor-type coupling constants, derived from β-ν angular correlation measurements are [12]:

$$\begin{aligned} |C_S/C_V| &< 0.08, \quad |C'_S/C_V| < 0.08\,, \\ |C_T/C_A| &< 0.13, \quad |C'_T/C_A| < 0.12\,. \end{aligned}$$

The constraints for scalar couplings include the recent result from the pure Fermi decay of ^{32}Ar [13]. Additional constraints are obtained from the ft-values of the superallowed $0^+ \to 0^+$ transitions, via the Fierz terms [6,7]. The constraints for tensor couplings are obtained from the analysis of the pure Gamow-Teller decay of ^{6}He [14]. These constraints allow one to still accommodate sizeable contributions of scalar and tensor interactions without affecting our conclusions on the phenomenology of semileptonic weak processes.

The result of the recent precise β-ν angular correlation experiment which determined the Doppler broadening of β-delayed protons in the Fermi β-decay of ^{32}Ar [13], is rather sensitive to the mass of ^{32}Ar, which was obtained from the Isobaric Multiplet Mass Equation (IMME). Therefore, a new experiment is planned now at GANIL [15]. There the β-ν correlation coefficient a will be obtained from the Doppler shift of the protons, which is less sensitive to the ^{32}Ar mass. This experiment has gained interest since it was shown recently that the IMME breaks down for $A = 33$ [16]. A direct mass measurement for ^{32}Ar is planned as well [17]. All other ongoing and planned β-ν correlation measurements in nuclear β-decay involve either laser-driven atom traps [18] or ion traps [19]. As for scalar current searches, at TRIUMF a first data set for $^{38\mathrm{m}}$K atoms in a Magneto Optical Trap (MOT) is being analyzed now [20], while at ISOLDE the Leuven group is installing a new set-up combining a Penning trap and a retardation spectrometer to measure the energy spectrum of the recoil ions resulting from ^{35}Ar β-decay [21]. As for tensor currents, a system with two optical traps for ^{82}Rb is running at Los Alamos [18,22], while at GANIL a Paul trap is being set up for a new experiment with ^{6}He [12]. Finally, two experiments are investigating a mixed transition and these are therefore sensitive to both scalar and tensor currents. At Berkeley the β-ν correlation is measured for optically trapped ^{21}Na [23], while at the ILL, Grenoble, this correlation will be measured in neutron decay using a retardation spectrometer [24]. All these experiments are taking data or scheduled to do so within the next two to three years, so that in a few years from now a wealth of new information on these exotic couplings could be available.

5 Right-handed currents

So-called left-right extensions of the Standard Model explain the seemingly maximal violation of parity in the weak interaction by introducing new W gauge bosons which couple to right-handed particles and which, by a spontaneous breaking of symmetry, acquire a mass that is larger than that of the well-known W boson which couples to left-handed particles [25]. Present constraints on right-handed currents from β-decay come from longitudinal positron polarization experiments [26,27], experiments in neutron decay (mainly the neutrino emission asymmetry B) [28], and measurements of the longitudinal polarization of positrons emitted by polarized nuclei [29–32]. New measurements of the last two types are in preparation at ILL (neutron B-correlation) [33] and at ISOLDE, with ^{118}Sb [34]. Although the present combined lower limit from β-decay for the mass of a W boson with right-handed couplings is about 310 GeV/c^2 (90% C.L.) when interpreted in the so-called manifest left-right symmetric model [31,32], while the corresponding lower limit from p-pbar collisions at Fermilab is 720 GeV/c^2 [35], results from β-decay and from collider experiments turn out to be complementary when interpreted in more general left-right symmetric extensions of the Standard Model [31,32].

6 Time-reversal violation

Direct searches for time-reversal violation (TRV) (and consequently CP-violation) via correlation experiments in β-decay require the measurement of correlations with three spin and/or momentum vectors. The D-triple correlation ($\mathbf{J} \times \mathbf{p} \times \mathbf{q}$) is sensitive to TRV in vector and axial-vector interactions and requires the use of mixed Fermi/Gamow-Teller transitions. This correlation was till now only measured in neutron decay ($D_{\mathrm{n}} = -0.0011(17)$ [36], $D_{\mathrm{n}} = 0.0022(30)$ [37]) and for ^{19}Ne ($D = 0.0001(6)$ [38]) and no sign for TRV was observed. New experiments in neutron decay are at present ongoing at ILL (TRINE experiment [39]) and at NIST, Gaithersburg (emiT experiment [40]). The R-triple correlation ($\sigma \cdot \mathbf{J} \times \mathbf{p}$) is sensitive to TRV scalar and tensor couplings. Only two experiments of this type were carried out till now, yielding $R(^{19}\mathrm{Ne}) = 0.079(53)$ [41] and $R(^{8}\mathrm{Li}) = 0.0016(22)$ [42]. Because of its high precision, the experiment with ^{8}Li resulted in very strong bounds for a TRV tensor interaction in β-decay. The experiment with ^{19}Ne was sensitive to both TRV scalar and tensor couplings but rather weak limits on these were obtained due to the limited experimental precision. A new R-correlation experiment in neutron decay is therefore in preparation now at the Paul Scherrer Institute [43].

Measurements of these D- and R-triple correlations are very difficult as they require the use of polarized nuclei and at the same time the determination of either the neutrino momentum (through the recoil ion; D-correlation) or of the transversal momentum of the beta-particle (R-correlation). It is finally to be noted that several other correlations are also sensitive to TRV couplings through final-state interaction effects (*e.g.*, the A-parameter, which measures $\mathbf{J} \times \mathbf{p}$ [32]) or through a quadratic dependence on the coupling constants (*e.g.*, the β-ν correlation coefficient a [13]).

Another way to search for T-violation in low-energy experiments is to search for a non-zero particle electric dipole moment (EDM) (see ref. [44]). The measurement consists in determining the precession frequency ω of a particle about the magnetic field in a region where both a magnetic field $\mathbf{B}$ and an electric field $\mathbf{E}$ are present and to compare the value obtained for the case where $\mathbf{B}$ and $\mathbf{E}$ are parallel ($\omega_+ = (\mu B + dE)h/J$) with the value when $\mathbf{B}$ and $\mathbf{E}$ are anti-parallel ($\omega_- = (\mu B - dE)h/J$), with μ the magnetic dipole moment and d the electric dipole moment of the particle. In the absence of an EDM, the difference of these two frequencies should be zero. Over the last 40 years, the upper limit for both the electron and the neutron EDM has been improved by about six orders of magnitude, thereby ruling out already several extensions of the Standard Model. Present upper limits are 6.3×10^{-26} e cm for the neutron EDM [45] and 4×10^{-27} e cm for the electron EDM [46]. New, even more sensitive experiments are planned at different institutes now. Of special interest could be measurements of nuclear EDMs, which have not received so much attention yet.

7 Setting the neutrino mass scale

Neutrino oscillation experiments have yielded clear evidence for differences in the squares of the neutrino masses [1], but the absolute neutrino mass scale is not accessible by these experiments. Since the search for neutrinoless double β-decay depends on assumptions on the neutrino particle character and on the neutrino mixing matrix, the only direct access to the mass scale is via the investigation of the kinematics of weak decays. The current best limit from tritium β-decay for the parameter $m_\nu^2 = \sum |U_{ei}|^2 m_i^2 = -1.6 \pm 2.5 \pm 2.1\ \mathrm{eV}^2/c^4$ (m_i = neutrino mass eigenstate) is obtained by the Mainz experiment [47,48]. The mass limit derived is $m_\nu < 2.2\ \mathrm{eV}/c^2$. A similar sensitivity is reached by the Troitsk experiment [49,50]. Based on the expertise of both groups, a dedicated experiment will now be set up and tested to push the sensitivity into the sub-eV range [51]. With this improvement of sensitivity by an order of magnitude it will be possible to cover the cosmologically relevant parameter space and to comment on different mass models for neutrinos. This experiment is presently the only attempt to reach this level of sensitivity.

8 Conclusion

In summary, a number of recent and ongoing or planned experiments probe different aspects of the weak-interaction structure. Precise ft-value determinations for superallowed $0^+ \rightarrow 0^+$ Fermi transitions, as well as lifetime and electron-asymmetry parameter measurements in neutron decay test the unitarity of the CKM quark-mixing matrix. Other experiments sensitive to the longitudinal or transversal polarization of beta-particles as well as several triple correlation experiments test parity violation and time-reversal violation. Several types of beta-neutrino correlation experiments probe the existence of scalar- and tensor-type charged weak currents. A new development in this respect are the set-ups using ion traps for weak-interaction studies that are currently being constructed. Several atom traps for correlation experiments in beta-decay as well as for atomic parity violation experiments are already operational, while others are being constructed. Finally, a new project is currently set up for measuring the neutrino mass in tritium beta-decay, trying to set the neutrino mass scale. These experiments will provide new and precise tests of the Standard Model in the low-energy semileptonic sector.

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