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Superallowed decays within and beyond the standard model

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Abstract This note reviews the role of superallowed transitions in determining the strength of the weak interaction among the lightest quarks and in searching for new physics beyond the standard electroweak model. The two sets of superallowed decays in nuclei considered here are pure Fermi and mirror transitions. The first have been scrutinized for more than 50 years. The most relevant results are presented and the role of the nucleus-dependent radiative correction and nucleus-independent inner radiative correction are reviewed. In this context, the systematic study of mirror transitions started about 15 years ago. Despite the significant progress made since then, the data is still limited by experimental uncertainties. Combining the results from all superallowed transitions, which are fully consistent, provides a test of unitarity of the first row of the Cabibbo-Kobayashi-Maskawa matrix, which displays a 2σ tension with the standard model.

1 Introduction

Experimental and theoretical studies of nuclear and neutron decays have been instrumental in establishing the structure of the electroweak sector of the Standard Model (SM). Despite its tremendous success, a number of fundamental questions remain unanswered such as the origin of maximal parity violation, the source of the matter-antimatter asymmetry in the Universe, the nature of dark matter and others, which necessarily involve New Physics (NP) and hence an extended theoretical framework.

Superallowed transitions in beta decay are considered to be the "cleanest" ones in terms of hadronic contributions arising from the nuclear medium. These transitions have been identified since the early days in the study of beta decay and have played a crucial role in determining the strength of weak processes involving the lightest u and d quarks. They offer today a sensitive window to search for NP through high precision measurements.

This paper reviews the contributions of pure Fermi and mirror superallowed transitions, to determine parameters within the SM or to constrain NP. It relies in particular on the results of four recent reviews and global analyses which can be found in Refs. [1–4]. Although neutron decay is the simplest mirror transition, the recent progress in neutron decay is not covered here besides mentioning the most relevant results.

2 Review of beta decay

Beta decay transitions for which the two leptons do not carry away any orbital angular momentum and for which there is no change in the parity of the nuclear states have traditionally been called *allowed transitions*. If in addition the decay occurs within an isospin multiplet, the transition is then termed *superallowed*.

From a nuclear structure perspective, the description of allowed transitions is simple because the nuclear matrix elements are independent of the orbital angular momentum of the leptons. The inclusion of angular momentum to higher orders in the lepton wave-functions gives rise to the higher degrees of forbiddenness. The maximum overlap between the initial and final nuclear states occurs when only a change in the third component of isospin takes place. Such "fast" tran-

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sitions were identified very early in the study of beta decay as a means to probe the weak interaction without being affected by hadronic effects induced by nuclear structure.

When the nuclear spins of both the initial and final states are zero, $\boldsymbol{J}_i = \boldsymbol{J}_f = \mathbf{0}$, the two leptons couple to a total spin $S = 0$ and the process is called a pure Fermi transition, whereas when the two nuclear spins are equal but different from zero, the two leptons can couple to $S = 0$ and $S = 1$. When this occurs within a same isospin doublet ($T = 1/2$) such transitions are called *mirror transitions*.

2.1 The beta decay strength

The strength of an interaction drives the decay time involved in a process. To eliminate the very strong dependence of the phase space integral on the available energy in a beta decay, one uses the ft value to characterize how fast a transition is, where f is the so-called statistical rate function and t is the partial half-life of the transition of interest. However, the ft value is still transition dependent and additional corrections need to be included. The expressions introduced in this section assume the SM framework and their modifications due to the possible presence of NP are explained in Sect. 2.2.

The beta decay rate from a nuclear state with partial half-life t, is given by

$$\lambda/\ln 2 = \frac{1}{t} = f\bar{\xi}_0 \frac{G_F^2 V_{ud}^2}{2K}, \tag{1}$$

where $G_F/(\hbar c)^3 = 1.1663787(6) \times 10^{-5}$ GeV^{-2} is the Fermi coupling constant, V_{ud} is the element of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix which describes the reduction of the coupling of the $W^{\pm}$ bosons to the u and d quarks and $K = 2\pi^3\hbar^7 \ln 2/\left(m_e^5 c^4\right)$ is a combination of physical constants. The quantity $\bar{\xi}_0$, like f, is also transition dependent and, for allowed transitions and, to lowest order, has the form

$$\bar{\xi}_0 = 2\bar{C}_V^2 M_F^2 + 2\bar{C}_A^2 M_{GT}^2, \tag{2}$$

where M_F and M_{GT} are the dominant matrix elements for Fermi and Gamow-Teller transitions and $\bar{C}_V$ and $\bar{C}_A$ are the relative amplitudes, in units of $\left(G_F V_{ud}/\sqrt{2}\right)$, of the terms driven by the vector and axial-vector operators of the beta decay Hamiltonian [1]. This expression implicitly assumes maximal parity violation for both interactions.

It is clear from Eqs. (1) and (2) that, at this level, the quantity which appears to be transition independent is the product $ft\bar{\xi}_0$. However, due to historical reasons and practices which are difficult to change, it is the product ft, along with some small corrections, which has traditionally been used in the surveys of pure Fermi transitions [2].

For allowed transitions, the Fermi integral, or statistical rate function, is given by

$$f = \int_1^{W_0} F(Z,W)S(Z,W)pW(W_0 - W)^2 dW\ , \tag{3}$$

where W is the total energy of the beta particle in units of the electron rest mass, $p = (W-1)^{1/2}$ is its momentum and W_0 is its maximal total energy. The function $F(Z,W)$ is the Fermi function and accounts for the Coulomb interaction with the electrostatic field of the nuclear daughter, with atomic number Z, and the function $S(Z,W)$ is a shape correction which accounts for screening of atomic electrons and higher order effects [5,6].

The partial half-life of a particular decay branch is determined from the half-life and the branching ratio, BR, to the particular final state. Since all practical transitions decay through β^+ emission, the partial half-life has to be corrected for the electron capture probability P_{EC}/P_{β^+} as

$$t = \frac{t_{1/2}}{BR}\left(1 + \frac{P_{EC}}{P_{\beta^+}}\right). \tag{4}$$

The electron capture probabilities can be calculated with sufficient accuracy so that the uncertainty on t is dominated by those on the half-life and branching ratio, which are extracted from decay spectroscopy measurements. It appears then from Eqs. (3) and (4) that a high precision extraction of the product ft requires three experimental properties to be measured: the half-life, $t_{1/2}$ of the decaying state, the branching ratio of the transition of interest, BR, and the maximum beta energy W_0 which is related to the masses of the initial and final nuclei. Since for allowed transitions, f varies with the 5th power of W_0, its precise determination requires very high precision mass determinations [7]. Typical relative uncertainties for the Fermi integral, f, are at the level of a few parts in 10^{-4}, with the most precise reaching 4.5×10^{-5} for ^{38m}K and ^{50}Mn.

The term $\bar{\xi}_0$ in Eq. (2) contains the dynamics of the nuclear process. It has been a common practice to include corrections which depend on the β-particle energy as factors along with others which are independent of the β-particle energy. The product $f\bar{\xi}_0$ can be generalized under the form [4]

$$f\bar{\xi}_c = 2(1+\delta_R')\Big[f_V \bar{C}_V^2 M_{F0}^2\left(1 + \delta_{NS}^V - \delta_C^V\right) + f_A \bar{C}_A^2 M_{GT0}^2 (1 + \delta_{NS}^A - \delta_C^A)\Big], \tag{5}$$

where the different terms are described here below. Under such conditions, it is finally the product $ft\bar{\xi}_c$ which is transition independent and only determined by the strength,

$$ft\bar{\xi}_c = \frac{2K}{G_F^2 V_{ud}^2}\ . \tag{6}$$

The correction terms in Eq. (5) are the nucleus-dependent radiative corrections, δ'_R and δ_{NS}, often called the "outer radiative corrections" since they are external to the weak interaction, and the isospin symmetry-breaking correction, δ_C. A nucleus-independent electroweak radiative correction, the "inner radiative correction", is embedded into $\bar{C}_V$ such that, in the limit of negligible momentum transfer $\bar{C}_V^2 = 1 + \Delta_R$.

The δ'_R term, which is typically of the order of 1.5 %, is a function of Z and W_0 and hence depends on the nucleus. It is mainly obtained from a standard QED calculation that has been completed to orders α and $Z\alpha^2$ and estimated to order $Z^2\alpha^3$ [8–10]. The δ_{NS} term which typically ranges from 0.02 to 0.40 %, requires a detailed nuclear-structure calculation, details on which can be found in Refs. [2,11–13]. Whereas δ'_R is the same for both Fermi and Gamow-Teller transitions, the contributions δ_{NS} and Δ_R differ for both types of transitions so that these terms include a superscript V or A to make the distinction.

For the isospin-symmetry breaking correction δ_C, which is due to the presence of Coulomb and other charge-dependent forces and ranges between 0.2 and 1.7 %, a distinction between Fermi and Gamow-Teller transitions should again be made. In the isospin-symmetry limit the Fermi matrix element, M_{F0}, is exactly known and given by $M_{F0}^2 = 2$ for a pure Fermi transition within a $T = 1$ multiplet and $M_{F0}^2 = 1$ for a mirror transition within a $T = 1/2$ multiplet. The isospin-symmetry breaking correction is then incorporated as

$$M_F^2 = M_{F0}^2 \left(1 - \delta_C^V\right). \tag{7}$$

In principle, a similar expression can be written for the Gamow-Teller matrix element but as its value in the isospin symmetry limit is not known, the distinction cannot be clearly made. The correction δ_C^V is typically separated into two parts

$$\delta_C^V = \delta_{C1}^V + \delta_{C2}^V. \tag{8}$$

The first component takes into account the charge-dependent configuration mixing and the resulting difference in wave functions for the parent and daughter nuclei. The second and largest component accounts for the differences in the single-particle neutron and proton radial wave functions.

The impact of the nuclear structure-dependent corrections, δ_{NS} and δ_C, and the inner radiative correction, Δ_R, on the extraction of the $ft\bar{\xi}_c$ values and V_{ud} is discussed below.

Having then determined the $ft\bar{\xi}_c$ values from a set of beta transitions, one can extract the product $G_F V_{ud}$ from Eq. (6). Since the Fermi coupling G_F is deduced most precisely from the measurement of the muon lifetime [14], the strength V_{ud} of the weak coupling to the lightest quarks can then be determined.

2.2 The decay strength beyond the SM

For the study of NP effects in beta decay, it is common to use the effective couplings introduced by Lee and Yang [15], just before the *V-A* nature of the weak interaction was established. The general Hamiltonian includes scalar, pseudo-scalar, vector, axial-vector and tensor interactions and was used to calculate the expressions of correlation coefficients [16] ignoring the contribution of the pseudo-scalar interaction. Today, the use of such formalism is justified because we know that the effects due to NP are small, and are described by the strength of the so-called "exotic" scalar, tensor and pseudo-scalar interactions.

When no assumptions are made about maximal parity violation and allowing for the presence of NP, the expression of $\bar{\xi}$ in Eq. (2) becomes [15]

$$\begin{aligned}\bar{\xi} = {} & M_F^2 \left[\bar{C}_S^2 + \bar{C}_S'^2 + \bar{C}_V^2 + \bar{C}_V'^2\right] \\ & + M_{GT}^2 \left[\bar{C}_A^2 + \bar{C}_A'^2 + \bar{C}_T^2 + \bar{C}_T'^2\right].\end{aligned} \tag{9}$$

Along with this change in the overall strength, the allowed spectrum in Eq. (3) receives an additional factor $(1 + b\gamma/W)$ which, after integration, results in a term such that Eq. (6) transforms into

$$ft\bar{\xi} = \frac{2K}{G_F^2 V_{ud}^2} \frac{1}{1 + b\gamma\langle 1/W\rangle}, \tag{10}$$

where $\langle 1/W\rangle$ denotes the averaging of the inverse of the beta particle energy over the statistical rate function and b is the Fierz interference term [16]

$$b\bar{\xi} = -2\left[M_F^2 \left(\bar{C}_V\bar{C}_S + \bar{C}'_V\bar{C}'_S\right) + M_{GT}^2 \left(\bar{C}_A\bar{C}_T + \bar{C}'_A\bar{C}'_T\right)\right], \tag{11}$$

with $\gamma = \sqrt{1 - \alpha^2 Z^2}$, α the fine structure constant, and, assuming time-reversal invariance, all couplings were taken to be real.

A non-zero Fierz term has then two main consequences on the properties discussed above: (i) it distorts the shape of the beta energy spectrum from the allowed distribution and (ii) it induces a transition dependence of the product $ft\bar{\xi}$ which are otherwise expected to be the same within the SM.

Pure Fermi transitions ($M_{GT} = 0$) are driven by the vector coupling and are sensitive to the presence of scalar couplings whereas mirror transitions are driven by both, the vector and axial-vector couplings and are then said to be mixed. They are sensitive to all couplings and depend on the nuclear matrix elements through the mixing ratio $\rho \approx \bar{C}_A M_{GT}/(\bar{C}_V M_F)$. The definition including radiative corrections is given in Eq. (17) below.

The procedure described in Sect. 2.1 to extract V_{ud} within the SM is affected by the non-standard terms. As a result, the quantity extracted is $V_{ud}(1 + \delta_{NP})$, where the δ_{NP} is a function of the nonstandard interactions which contribute to Eq. (9). A non-zero value for this correction would entail an apparent violation of the CKM unitarity.

3 Fermi transitions

Soon after establishing the *V-A* nature of the weak interaction, it was postulated that the vector part of the interaction was independent of the nuclear transition, the so-called *Conservation of the Vector Current* (CVC) [17]. One of the consequences of the CVC is that the $ft\bar{\xi}_c$ values for all $T = 1$ Fermi transitions must be the same. This has enabled the extraction of parameters within the SM and also the search for NP.

3.1 V_{ud} within the SM from Fermi transitions

At the fundamental level of leptons and quarks, the vector strength is driven by the product $G_F V_{ud}$. For pure Fermi transitions one has $M_{F0} = \sqrt{2}$, $M_{GT} = 0$, and $f_V = f$. The correction to the ft values becomes, within the SM, $\bar{\xi}_c \to \bar{\xi}_F = 4(1+\delta'_R)(1+\delta^V_{NS}-\delta^V_C)(1+\Delta^V_R)$. The Fermi matrix element and the three correcting factors have traditionally been split such that the quoted value for pure Fermi transitions is defined as [2,18]

$$\begin{aligned}\mathcal{F}t^{0^+\to 0^+} &= ft(1+\delta'_R)(1+\delta^V_{NS}-\delta^V_C)\\ &= \frac{K}{2G_F^2 V_{ud}^2(1+\Delta^V_R)}.\end{aligned} \tag{12}$$

The precise determination of a single $\mathcal{F}t$ value would be sufficient to extract V_{ud}. For several pure Fermi transitions, the careful selection of the relevant experimental data and the critical studies of the associated theoretical corrections have been carried out by Hardy and Towner over almost five decades. The left panel in Fig. 1 shows the recommended values produced by those surveys along with their associated total uncertainties as a function of time.

It is observed that from 1990 on, the central values are about 10 s smaller than those published in the 70's. It was then stated that the largest shift resulted from revisions in the calculations of δ'_R [19]. This also coincides with the consideration of the unitarity test of the first row of CKM matrix performed since then using the data from these transitions. From 1990 on, the central values are relatively stable and their total uncertainties became smaller until the result quoted in 2015. The last evaluation [2] quotes however a total uncertainty which is a factor of 2.6 larger than the 2015 survey [20]. This is associated with theoretical uncertainties of the radiative correction δ^V_{NS} whereas the statistical uncertainty of the experimental data has slightly improved. For δ^V_{NS}, two small contributions in addition to the traditional ones were recently pointed out in Refs. [21] and [13]. For δ^V_C, alternative approaches have been reported in Refs. [22] and [23].

The 2020 survey of data produced the following values [2]

$$\bar{\mathcal{F}t}^{0^+\to 0^+} = 3072.24 \pm 1.85 \text{ s}, \tag{13}$$

$$|V_{ud}| = 0.97373 \pm 0.00031 \quad (\text{Fermi}). \tag{14}$$

When combined with the values of V_{ub} and V_{us}, the test of unitarity resulting from the first row of the CKM matrix displays a 2.2σ tension [28]. This is due to a reduction of the central value of V_{ud} which is not concomitant with a change in the $\bar{\mathcal{F}t}$ value (Fig. 1 left panel). It appears that recent calculations of Δ^V_R [21,29–33] yielded a more precise but also larger value of the electroweak radiative correction than the previously adopted one [34], reducing thereby the value of V_{ud} [Eq. (12)]. The unitarity test will be reviewed below when considering the input from all superallowed transitions.

3.2 Constraints on scalar couplings

When allowing the presence of exotic scalar interactions and neglecting quadratic terms, the expression of $\mathcal{F}t$ in Eq. (12) is extended following Eq.(10) to become

$$\mathcal{F}t^{0^+\to 0^+}_{\text{BSM}} \approx \frac{K}{2G_F^2 V_{ud}^2(1+\Delta^V_R)}\frac{1}{1+b_F\gamma\langle 1/W\rangle}, \tag{15}$$

where b_F is the Fierz term for pure Fermi transitions. Assuming all couplings to be real and maximal parity violation for all interactions, the Fierz term translates to linear order into $b_F \approx -2C_S/C_V$. The weighting factors $\langle 1/W\rangle$ appear to decrease with the mass or atomic number of the decaying nucleus because the endpoint energies, W_0, increase [2]. The departure from a constant of Eq. (15) enables then constraining the presence of a non-zero value for b_F.

It is impressive that the first systematic determinations of ft values in pure Fermi transitions in 1958 [35] already attempted using the Fierz term to determine the nature of the weak interaction. The first constraint obtained by Gerhart was $|b_F| < 0.12$ [35].

The right panel in Fig. 1 shows the evolution of the 90% C.L. constraint on the scalar coupling extracted from the analyses of the $\mathcal{F}t$ values, over the same time interval than the left panel. It is seen that in 1975, this procedure provided a value of b_F consistent with zero [24] even when the absolute average $\mathcal{F}t$ value was off by 10 s compared with the currently recommended value. It is the internal consistency among the $\mathcal{F}t$ values together with the different weighting factors $\langle 1/W\rangle$ which provide sensitivity to the Fierz term. It is also noted that the limit of a few 10^{-3} obtained on the scalar coupling has remained rather constant over the past three decades. This calls the exploration of alternative means

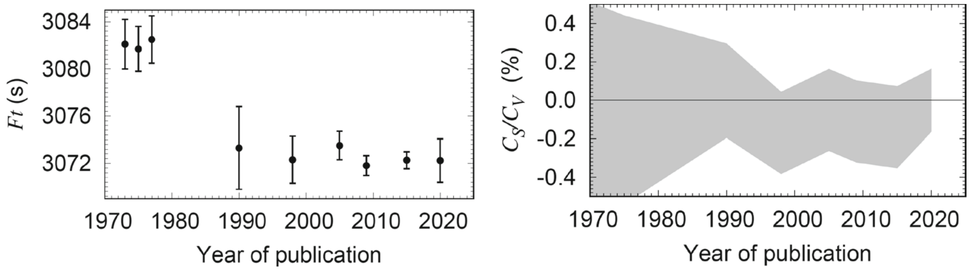

Fig. 1 Left: evolution of the average $\mathcal{F}t^{0^+\to 0^+}$ values over about 50 years extracted from global surveys performed by Hardy and Towner. The error bars include both, the statistical and the systematic uncertainties which were sometimes combined linearly and sometimes quadratically in the recommended values. The data are from Refs. [2,5,18–20,24–27]. Right: Evolution of the 90% C.L. constraint on the scalar coupling obtained from some of the surveys for which the $\mathcal{F}t$ values are shown in the left panel

to possibly improve the sensitivity on the Fierz term in pure Fermi transitions.

3.3 Global fits

The procedure described in Sect. 3.1 to extract V_{ud} assumes $b_F = 0$, whereas the procedure in Sec. 3.2 to extract b_F assumes some constant value for V_{ud}. This is how those analysis have traditionally been performed in the past [2,5,19,20]. The two parameters, V_{ud} and b_F, are however fully correlated and it is appropriate to extract them including their correlation. Such a procedure has been performed in Ref. [1] for the first time, using the values of the 2015 survey [20] and the then adopted value for Δ_R^V [34]. In particular, due to the correlation, the uncertainty on the value of V_{ud} extracted from such a global fit, where both parameters are free, is a factor of about 3 larger than the value extracted within the SM [1]. The inclusion of the correlation allows us to extract the value for V_{ud} in a framework involving new physics.

4 Mirror transitions

As already indicated in Sect. 2.2, within the SM, superallowed mirror transitions involve both, vector and axial-vector interactions and are therefore mixed. Beyond the SM, they can probe not only scalar but, in addition, also tensor interactions as possible signatures of NP. The occurrence of the Gamow-Teller matrix element, which cannot be calculated with sufficient accuracy for precision tests, adds a complication for the use of mirror transitions.

The consideration of mirror transitions to extract V_{ud} is more recent [36] than the use of Fermi transitions but considerable progress has been made for the construction of a robust data set and to address the required theoretical corrections [4,37].

4.1 V_{ud} within the SM from mirror transitions

For mixed transitions in which both, the Fermi and Gamow-Teller matrix elements can contribute, the product $f t \bar{\xi}_c$ can be written as

$$f t \bar{\xi}_c = 2 f_V t \bar{C}_V^2 M_{F0}^2 (1+\delta'_R)(1+\delta^V_{NS}-\delta^V_C)\left[1+\frac{f_A}{f_V}\rho^2\right] \tag{16}$$

where

$$\rho = \frac{\bar{C}_A M_{GT0}}{\bar{C}_V M_{F0}}\left[\frac{(1+\delta^A_{NS}-\delta^A_C)}{(1+\delta^V_{NS}-\delta^V_C)}\right]^{1/2} \approx \frac{\bar{C}_A M_{GT0}}{\bar{C}_V M_{F0}}, \tag{17}$$

is the Gamow-Teller-to-Fermi mixing ratio introduced above, but including here higher order corrections.

The expression for Fermi transitions can be recovered from Eq. (16) by setting $M_{F0}^2 = 2$ and $\rho = 0$. In a mixed transition within an isospin doublet ($T = 1/2$) one has $M_{F0}^2 = 1$ and ρ can possibly be different from zero. The following expressions can then be derived [4]

$$\frac{f t \bar{\xi}_c}{1+\Delta_R^V} = 2 f_V t (1+\delta'_R)(1+\delta^V_{NS}-\delta^V_C)\left[1+\frac{f_A}{f_V}\rho^2\right] \tag{18}$$

$$\equiv \mathcal{F}t^{\text{mirror}}\left[1+\frac{f_A}{f_V}\rho^2\right] = 2\mathcal{F}t^{0^+\to 0^+} \tag{19}$$

It appears then that, to extract V_{ud}, mirror transitions require two additional parameters relative to pure Fermi ones: f_A which, like f_V, is calculated theoretically using the value of the end-point energy, and ρ which is extracted from independent measurements of other observables in the same decay.

Using the approximation $f_A \approx f_V$ in Eq. (19), Masson and Quin extracted the values of ρ from the calculated $\mathcal{F}t$ values in Fermi transitions and in the mirror transitions of the neutron, ^{17}F, ^{19}Ne, ^{29}P and ^{35}Ar [38]. From the values of ρ

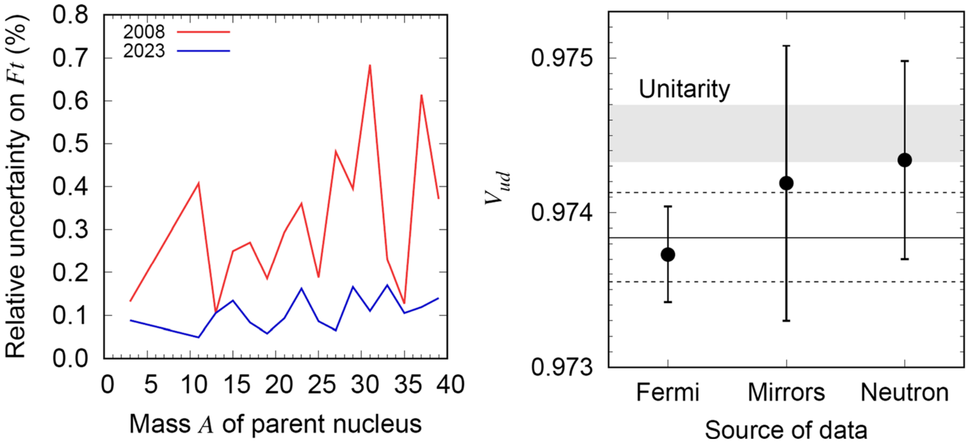

Fig. 2 Left: evolution of the relative uncertainties on $\mathcal{F}t$ values in mirror transitions up to mass $A = 39$ from the 2008 survey of Ref. [37] (red) and from the 2023 survey of Ref. [4] (blue). Right: current values of $|V_{ud}|$ from the three sets of data in superallowed transitions. The grey band shows the value deduced from the unitarity condition and the dotted lines show the interval of the mean value from the three sets

they then calculated the expected value of the β-asymmetry parameter, A [16], and compared these with experimental results. This provided a first test of CVC in that set of mirror transitions, although this implicitly included the test of CVC in the Fermi transitions.

To extract V_{ud} from mirror transitions independently from Fermi ones, it is necessary to include all corrections which appear in Eq. (18). Those corrections were made available in Ref. [37] enabling a formal test of CVC and the first extraction of V_{ud} [36]. The analysis included updated $\mathcal{F}t$ values as well as the results from measurements of the $\beta\nu$-angular correlation, a, the β-asymmetry parameter, A and the ν-asymmetry parameter, B, to extract the mixing ratios [36].

Since then, significant progress has been made in the determination of $\mathcal{F}t$ values from measurements of spectroscopic quantities. The $\mathcal{F}t$ values currently have relative uncertainties smaller than 0.2% for all transitions up to ^{39}Ca [4]. The left panel in Fig. 2 illustrates the evolution in precision between 2008 and 2023. All transitions have now reached a level comparable to those of ^{13}N, ^{33}Cl and ^{35}Ar, which were already rather precise and did not improved much.

But an improved extraction of V_{ud} requires also high precision measurements of correlation parameters in order to extract ρ, and the progress here has been rather moderate. Since the first determination of V_{ud} in 2009 [36], only one new measurement has been performed to extract ρ. This was the β-asymmetry parameter in ^{37}K decay [39]. The experiment measured the absolute β asymmetry as a function of the β-particle energy from ^{37}K atoms stored in a magneto-optical trap. For this purpose, the polarization of the sample has been determined to an unprecedented level of precision. In the same context, an old measurement of the β-asymmetry parameter performed in ^{19}Ne decay has been revisited but has not yet been published [40]. Other correlation measurements have been performed using trapped ^{19}Ne and ^{35}Ar ions but they were either analyzed within the SM for other purposes [41,42] or the associated uncertainty was too large to have any significant impact [43].

An update of the data from six mirror transitions has been provided in Ref. [3] and the data were used in global fits under several assumptions. In a most recent survey [4], the data from mirror transitions has been reviewed and selected following standard criteria. For the six mirror transitions included in Ref. [3], the $\mathcal{F}t$ values for ^{17}F, ^{35}Ar, and ^{37}K extracted in Ref. [4] have uncertainties which are respectively a factor of 1.4, 1.2 and 1.5 smaller than those quoted in Ref. [3]. The data from ^{17}F was however not used in Ref. [4] for further analysis. The average values quoted in Ref. [4] of $\mathcal{F}t^{\text{mirror}}(1 + f_A\rho^2/f_V)$ in Eq. (19), which is noted $\mathcal{F}t_0$, and of $|V_{ud}|$, resulting from five mirror decays, where the values of ρ were extracted from measurements of various correlation coefficients, are

$$\mathcal{F}t_0 = 6138.7 \pm 11.1 \text{ s}, \tag{20}$$

$$|V_{ud}| = 0.97419 \pm 0.00089 \quad \text{(mirrors)}. \tag{21}$$

The value in Eq. (21) was deduced using the same weighted average for the nucleus-independent inner radiative correction than the one used to extract the value in Eq. (14), i.e. $\Delta_R^V = 0.02454(19)$ [2,30,31].

4.2 Superallowed transitions and CKM unitarity

For comparison purposes, the value extracted in Ref. [4] from neutron decay data, using the same inner radiative correction indicated above, is

$$|V_{ud}| = 0.97434 \pm 0.00064 \quad \text{(neutron)}. \tag{22}$$

In contrast to the value quoted in Ref. [3], this value includes also new results for the $\beta\nu$-angular correlation [44] and for the neutron lifetime [45]. The approach used in Ref. [4] is also more conservative in the sense that a factor was properly applied to account for the internal inconsistency among the extracted values for ρ.

Table 1 Values of V_{ud} resulting from the three data sets, using the indicated value for the nucleus independent inner radiative correction [2,30,31]

Δ_R^V	0.02454 (19)
Fermi	0.97373 (31)
Mirrors	0.97419 (89)
Neutron	0.97434 (64)
Superallowed	0.97384 (29)

The three results quoted in Eqs. (14), (21) and (22) are statistically independent (except for the common effect Δ_R^V) and display an excellent internal consistency (right panel of Fig. 2). The impact on V_{ud} of the different values of Δ_R^V has been discussed in more detail in Ref. [3] along with a parametrization that consistently included this common systematic correction in global fits.

Table 1 summarizes the results discussed above. The second column reproduces the individual values quoted in Eqs. (14), (21) and (22). The value on the line noted "Superallowed" results from a fit of the $ft\bar{\xi}_c$ values from all three sources to which the correction with the value of Δ_R^V was then applied [Eq. (18)]. It is seen that the data from mirror transitions and from the neutron tend to increase the central value obtained from Fermi transitions but their statistical weight is limited.

Using the values of $|V_{us}| = 0.22430(80)$ and $|V_{ub}| = 0.00382(20)$ recommended by the Particle Data Group [28] along with the value $|V_{ud}| = 0.97384(29)$ from all superallowed transitions (Table 1), the unitarity sum from the first row of the CKM matrix reads

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99869 \pm 0.00067, \qquad (23)$$

and shows a 2σ tension with the standard model. The values of $|V_{ud}|$ in Table 1 are shown in the right panel of Fig. 2. The value of the mean from all superallowed transitions is also shown by the band with dashed lines and the value deduced from the unitarity condition is shown by the grey band.

4.3 Constraints on exotic couplings

Precision measurements from nuclear mirror transitions have also been considered in the past as sensitive means to constrain signatures from NP. The combination of the β-asymmetry parameter with the $\mathcal{F}t$ values in ^{19}Ne decay and in pure Fermi transitions served for instance to constrain deviations from maximal parity violation in a model dependent way [46]. The measurement of the ν-asymmetry parameter [47] and the β-asymmetry parameter [39] in ^{37}K decay provided also windows to constrain models restoring the parity symmetry. Measurements of the $\beta\nu$-angular correlation in ^{21}Na decay enabled to constrain the couplings describing scalar and tensor interactions [48], although the analysis reported there is inconsistent since it assumed the presence of NP in the correlation parameter but not in the $\mathcal{F}t$ values from which the mixing ratio was extracted.

This point deserves some attention related to the use of the mixing ratio. With the V_{ud} value from superallowed decays and the $\mathcal{F}t$ values of mirror decays, it is possible to extract, within the SM, precise values of the mixing ratios using Eq. (19) and from there to provide precise SM values for various correlation coefficients. This was performed in Ref. [37] and updated in Ref. [49]. When confronted to a new measurement, the calculated SM value of a correlation coefficient would enable to indicate a possible deviation but cannot be used to extract or constraint new interactions using directly the expression of the correlation coefficient from Ref. [16]. Such an analysis was performed in Ref. [48] and is inconsistent for the reason mentioned above. When new interactions are assumed to be present, the analysis has to be made with a global fit, in which the mixing ratios and the amplitudes of non-standard couplings are extracted simultaneously, so that the extracted mixing ratios take into account the contributions of new interactions to the $\mathcal{F}t$ values.

The first global fit using consistently the data from the mirror decays of ^{17}F, ^{19}Ne, ^{21}Na, ^{29}P and ^{35}Ar was recently reported in Ref. [3]. The analysis included the most recent data of $\mathcal{F}t$ values in pure Fermi transitions, the most sensitive data in neutron decay as well as measurements of correlation parameters in pure Fermi and pure Gamow-Teller transitions. The update of data for mirror transitions has been surveyed in Ref. [4] and the details were given above.

The global fits from Ref. [3] were made within three scenarios: (i) in the SM framework; (ii) assuming the NP manifest through interactions involving only left-handed neutrinos; and (iii) assuming the NP interactions involve both, left- and right-handed neutrinos. It is the most comprehensive analysis of beta decay data realized so far, which also includes neutron data. The analysis showed that, although data from mirror transitions alone are able to constrain parameters describing both scalar and tensor interactions in scenario (ii), their sensitivity is about an order of magnitude smaller than the one of data from pure Fermi transitions and neutron decay, as used in the global fit of Ref. [1]. The main reason is that the relative uncertainties of correlation measurements in mirror transitions are too large compared to those in neutron decay, having therefore a limited constraining power. The global fit performed under scenario *iii)*, requires a minimization with 14 free parameters. These are 8 parameters related to the couplings $\bar{C}_S$, $\bar{C}'_S$, $\bar{C}_V$, $\bar{C}'_V$, $\bar{C}_A$, $\bar{C}'_A$, $\bar{C}_T$, and $\bar{C}'_T$, in Eqs. (9) and (11) and the 6 mixing ratios of the mirror transitions. The outcome of the fit showed that data from mirror transitions have a significant effect in constraining the couplings, with improvement factors ranging from 1.6 to 2.8 for seven out of the eight couplings [3].

A new global fit analysis including mirror transitions, which incorporates for the first time the effect of NP interactions at the subleading order in recoil momentum, has been reported in Ref. [50]. In particular, this work studied the effects of pseudo-scalar interactions between nucleons and leptons. It was found that nuclear decays set a robust constraint on these interactions, which allows one to set simultaneous bounds on the exotic pseudo-scalar, scalar, and tensor currents. Furthermore, the recoil level analysis allows one to experimentally test the CVC predictions regarding weak magnetism. The current data shows a 3σ evidence for a non-zero value of nucleon-level weak magnetism, independently of theory predictions. The evidence is dominated by the neutron decay measurements (lifetime and β-asymmetry), and is further strengthened by mirror decays. Yet another recoil-level effect discussed in Ref. [50] is the so-called induced tensor interactions. The isospin symmetry of QCD predicts that these interactions should be suppressed so as to give negligible contributions to observables, however the current data show a 1.8σ preference for a non-zero value.

5 Summary and outlook

Superallowed transitions have been instrumental in establishing the nature of the weak interaction and provide today a sensitive window to search for new physics beyond the standard model. The detailed study of Fermi transitions with the purpose to extract the strength of the effective vector coupling, has been ongoing for about 50 years. Since 1990, the value of $|V_{ud}|$ has been determined with ever increased precision but recent revisits of the nucleus-dependent outer radiative correction resulted in a factor of 2.6 increase on the uncertainty of the average $\mathcal{F}t$ value [2]. This indicates underestimates of the uncertainties of such contributions in previous surveys. To a lesser extent, the reconsideration of the nucleus-independent radiative correction also had an impact by lowering the central values of $|V_{ud}|$ and putting the CKM unitarity under some stress. This underlines the utmost importance of theoretical considerations in order to converge to values for these corrections with well quantified uncertainties.

For more than three decades, Fermi transitions have provided the tightest constraints on the couplings of exotic scalar interactions involving left-handed neutrinos. The progress has however been rather modest and the question arises about exploring alternative routes to make a step in sensitivity. This is for instance being considered in measurements of β-delayed protons correlations in the pure Fermi decay of ^{32}Ar [51]. Another possible avenue is offered by the measurement of the β-energy spectrum in the decay of ^{26m}Al. This isotope can be copiously produced in radioactive beam facilities where a calorimetry type technique [52] can be implemented. The absence of any subsequent γ ray provides a clean decay environment such that the two annihilation photons are to be detected in coincidence with external ancillary detectors.

The systematic consideration of mirror transitions to extract the strength of the vector interaction is more recent. The improvements in the determination of precise $\mathcal{F}t$ values has been fast, with many new inputs from nuclear spectroscopy experiments [4]. However, the extraction of $|V_{ud}|$ also requires the precise determination of the Gamow-Teller-to-Fermi mixing ratios from correlations measurements and the number of new results in the past decade has here been limited. A rather extensive list of ongoing and planned experiments in neutron and nuclear decays was presented in Ref. [1] and, to a large extent, is still valid today. It is strongly suited that some of those concerning nuclear mirror transitions be successful and completed soon.

Mirror transitions have been incorporated in global analyses to search for new physics [3], with their strongest impact in a scenario with interactions involving left- and right-handed neutrinos. Since the effect of recoil order and radiative corrections can accurately be included in such transitions [4], the impact of new physics at the subleading order in recoil has recently been explored [50]. Their study is bringing new light in the tests of CVC predictions and in the determination or constraints of genuine or induced couplings.

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References

1. M. Gonzalez-Alonso, O. Naviliat-Cuncic, N. Severijns, New physics searches in nuclear and neutron β decay. Prog. Part. Nucl. Phys. **104**, 165 (2019). https://doi.org/10.1016/j.ppnp.2018.08.002
2. J.C. Hardy, I.S. Towner, Superallowed $0^+ \rightarrow 0^+$ nuclear β decays: 2020 critical survey, with implications for V_{ud} and CKM unitarity. Phys. Rev. C **102**, 045501 (2020). https://doi.org/10.1103/PhysRevC.102.045501

3. A. Falkowski, M. González-Alonso, O. Naviliat-Cuncic, Comprehensive analysis of beta decays within and beyond the Standard Model. J. High Energ. Phys. **2021**, 126 (2021). https://doi.org/10.1007/JHEP04(2021)126
4. N. Severijns, L. Hayen, V. De Leebeeck, S. Vanlangendonck, K. Bodek, D. Rozpedzik, I.S. Towner, $\mathcal{F}t$ values of the mirror β transitions and the weak-magnetism-induced current in allowed nuclear β decay. Phys. Rev. C **107**, 015502 (2023). https://doi.org/10.1103/PhysRevC.107.015502
5. J.C. Hardy, I.S. Towner, Superallowed $0^+ \rightarrow 0^+$ nuclear β decays: a critical survey with tests of the conserved vector current hypothesis and the standard model. Phys. Rev. C **71**, 055501 (2005). https://doi.org/10.1103/PhysRevC.71.055501
6. L. Hayen, N. Severijns, K. Bodek, D. Rozpedzik, X. Mougeot, High precision analytical description of the allowed β spectrum shape. Rev. Mod. Phys. **90**, 015008 (2018). https://doi.org/10.1103/RevModPhys.90.015008
7. J. Dilling, K. Blaum, M. Brodeur, S. Eliseev, Penning-trap mass measurements in atomic and nuclear physics. Annu. Rev. Nucl. Part. Sci. **68**(1), 45–74 (2018). https://doi.org/10.1146/annurev-nucl-102711-094939
8. A. Sirlin, R. Zucchini, Accurate verification of the conserved-vector-current and standard-model predictions. Phys. Rev. Lett. **57**, 1994–1997 (1986). https://doi.org/10.1103/PhysRevLett.57.1994
9. W. Jaus, G. Rasche, Radiative corrections to 0^+-0^+ β transitions. Phys. Rev. D **35**, 3420–3422 (1987). https://doi.org/10.1103/PhysRevD.35.3420
10. A. Sirlin, Remarks concerning the O($Z\alpha^2$) corrections to Fermi decays, conserved-vector-current predictions, and universality. Phys. Rev. D **35**, 3423–3427 (1987). https://doi.org/10.1103/PhysRevD.35.3423
11. I.S. Towner, J.C. Hardy, Improved calculation of the isospin-symmetry-breaking corrections to superallowed Fermi β decay. Phys. Rev. C **77**, 025501 (2008). https://doi.org/10.1103/PhysRevC.77.025501
12. I.S. Towner, J.C. Hardy, The evaluation of V_{ud} and its impact on the unitarity of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix. Rep. Prog. Phys. **73**(4), 046301 (2010). https://doi.org/10.1088/0034-4885/73/4/046301
13. M. Gorchtein, γW box inside out: nuclear polarizabilities distort the beta decay spectrum. Phys. Rev. Lett. **123**, 042503 (2019). https://doi.org/10.1103/PhysRevLett.123.042503
14. V. Tishchenko, S. Battu, R.M. Carey, D.B. Chitwood, J. Crnkovic, P.T. Debevec, S. Dhamija, W. Earle, A. Gafarov, K. Giovanetti, T.P. Gorringe, F.E. Gray, Z. Hartwig, D.W. Hertzog, B. Johnson, P. Kammel, B. Kiburg, S. Kizilgul, J. Kunkle, B. Lauss, I. Logashenko, K.R. Lynch, R. McNabb, J.P. Miller, F. Mulhauser, C.J.G. Onderwater, Q. Peng, J. Phillips, S. Rath, B.L. Roberts, D.M. Webber, P. Winter, B. Wolfe, Detailed report of the MuLan measurement of the positive muon lifetime and determination of the Fermi constant. Phys. Rev. D **87**, 052003 (2013). https://doi.org/10.1103/PhysRevD.87.052003
15. T.D. Lee, C.N. Yang, Question of parity conservation in weak interactions. Phys. Rev. **104**, 254 (1956). https://doi.org/10.1103/PhysRev.104.254
16. J.D. Jackson, S.B. Treiman, H.W. Wyld Jr., Coulomb corrections in allowed beta transitions. Nucl. Phys. **4**, 206 (1957). https://doi.org/10.1016/0029-5582(87)90019-8
17. R.P. Feynman, M. Gell-Mann, Theory of the Fermi interaction. Phys. Rev. **109**, 193 (1958). https://doi.org/10.1103/PhysRev.109.193
18. I.S. Towner, J.C. Hardy, Superallowed $0^+ \rightarrow 0^+$ nuclear β-decays. Nucl. Phys. A **205**(1), 33–55 (1973). https://doi.org/10.1016/0375-9474(73)90118-8
19. J.C. Hardy, I.S. Towner, V.T. Koslowsky, E. Hagberg, H. Schmeing, Superallowed $0^+ \rightarrow 0^+$ nuclear β-decays: a critical survey with tests of cvc and the standard model. Nucl. Phys. A **509**(3), 429–460 (1990). https://doi.org/10.1016/0375-9474(90)90086-2
20. J.C. Hardy, I.S. Towner, Superallowed $0^+ \rightarrow 0^+$ nuclear β decays: 2014 critical survey, with precise results for V_{ud} and CKM unitarity. Phys. Rev. C **91**, 025501 (2015). https://doi.org/10.1103/PhysRevC.91.025501
21. C.-Y. Seng, M. Gorchtein, M.J. Ramsey-Musolf, Dispersive evaluation of the inner radiative correction in neutron and nuclear β decay. Phys. Rev. D **100**, 013001 (2019). https://doi.org/10.1103/PhysRevD.100.013001
22. W. Satula, P. Baczyk, J. Dobaczewski, M. Konieczka, No-core configuration-interaction model for the isospin- and angular-momentum-projected states. Phys. Rev. C **94**, 024306 (2016). https://doi.org/10.1103/PhysRevC.94.024306
23. L. Xayavong, N.A. Smirnova, Radial overlap correction to superallowed $0^+ \rightarrow 0^+$ β decay reexamined. Phys. Rev. C **97**, 024324 (2018). https://doi.org/10.1103/PhysRevC.97.024324
24. J.C. Hardy, I.S. Towner, Superallowed $0^+ \rightarrow 0^+$ nuclear β-decays and Cabibbo universality. Nucl. Phys. A **254**(2), 221–240 (1975). https://doi.org/10.1016/0375-9474(75)90214-6
25. I.S. Towner, J.C. Hardy, M. Harvey, Analogue symmetry breaking in superallowed Fermi β-decay. Nucl. Phys. A **284**(2), 269–281 (1977). https://doi.org/10.1016/0375-9474(77)90123-3
26. I.S. Towner, J.C. Hardy. The current status of V_{ud}. in *Proceedings of the V International WEIN Symposium: Physics Beyond the Standard Model, Santa Fe, 1998*, ed. by P. Herczeg, C.M. Hoffman, H.V. Klapdor-Kleingrothaus (World Scientific, Singapore 1999), pp. 338–359. https://arxiv.org/abs/nucl-th/9809087v1 (1998)
27. J.C. Hardy, I.S. Towner, Superallowed $0^+ \rightarrow 0^+$ nuclear β decays: A new survey with precision tests of the conserved vector current hypothesis and the standard model. Phys. Rev. C **79**, 055502 (2009). https://doi.org/10.1103/PhysRevC.79.055502
28. R.L. Workman et al., Review of particle physics. Prog. Theor. Exp. Phys. **2022**, 083–01 (2022). https://doi.org/10.1093/ptep/ptac097
29. C.-Y. Seng, M. Gorchtein, H.H. Patel, M.J. Ramsey-Musolf, Reduced hadronic uncertainty in the determination of V_{ud}. Phys. Rev. Lett. **121**, 241804 (2018). https://doi.org/10.1103/PhysRevLett.121.241804
30. C.-Y. Seng, X. Feng, M. Gorchtein, L.-C. Jin, Joint lattice QCD-dispersion theory analysis confirms the quark-mixing top-row unitarity deficit. Phys. Rev. D **101**, 111301 (2020). https://doi.org/10.1103/PhysRevD.101.111301
31. A. Czarnecki, W.J. Marciano, A. Sirlin, Radiative corrections to neutron and nuclear beta decays revisited. Phys. Rev. D **100**, 073008 (2019). https://doi.org/10.1103/PhysRevD.100.073008
32. K. Shiells, P.G. Blunden, W. Melnitchouk, Electroweak axial structure functions and improved extraction of the V_{ud} CKM matrix element. Phys. Rev. D **104**, 033003 (2021). https://doi.org/10.1103/PhysRevD.104.033003
33. L. Hayen, Standard model $\mathcal{O}(\alpha)$ renormalization of g_A and its impact on new physics searches. Phys. Rev. D **103**, 113001 (2021). https://doi.org/10.1103/PhysRevD.103.113001
34. W.J. Marciano, A. Sirlin, Improved calculation of electroweak radiative corrections and the value of V_{ud}. Phys. Rev. Lett. **96**, 032002 (2006). https://doi.org/10.1103/PhysRevLett.96.032002
35. J.B. Gerhart, Fierz interference of the Fermi interactions in beta decay. Phys. Rev. **109**, 897–900 (1958). https://doi.org/10.1103/PhysRev.109.897
36. O. Naviliat-Cuncic, N. Severijns, Test of the conserved vector current hypothesis in $T = 1/2$ mirror transitions and new determination of V_{ud}. Phys. Rev. Lett. **102**, 142302 (2009). https://doi.org/10.1103/PhysRevLett.102.142302
37. N. Severijns, M. Tandecki, T. Phalet, I.S. Towner, $\mathcal{F}t$ values of the $T = 1/2$ mirror β transitions. Phys. Rev. C **78**, 055501 (2008). https://doi.org/10.1103/PhysRevC.78.055501

38. G.S. Masson, P.A. Quin, Measurement of the asymmetry parameter for ^{29}P β decay. Phys. Rev. C **42**, 1110–1119 (1990). https://doi.org/10.1103/PhysRevC.42.1110
39. B. Fenker, A. Gorelov, D. Melconian, J.A. Behr, M. Anholm, D. Ashery, R.S. Behling, I. Cohen, I. Craiciu, G. Gwinner, J. McNeil, M. Mehlman, K. Olchanski, P.D. Shidling, S. Smale, C.L. Warner, Precision measurement of the β asymmetry in spin-polarized ^{37}K decay. Phys. Rev. Lett. **120**, 062502 (2018). https://doi.org/10.1103/PhysRevLett.120.062502
40. D. Combs, G. Jones, W. Anderson, F. Calaprice, L. Hayen, A. Young. A look into mirrors: a measurement of the β-asymmetry in ^{19}Ne decay and searches for new physics. (2020). arXiv:2009.13700
41. C. Couratin, X. Fabian, B. Fabre, B. Pons, X. Fléchard, E. Liénard, G. Ban, M. Breitenfeldt, P. Delahaye, D. Durand, A. Méry, O. Naviliat-Cuncic, T. Porobic, G. Quéméner, D. Rodríguez, N. Severijns, J.-C. Thomas, S. Van Gorp, Electron shakeoff following the β^+ decay of trapped ^{35}Ar$^+$ ions. Phys. Rev. A **88**, 041403 (2013). https://doi.org/10.1103/PhysRevA.88.041403
42. X. Fabian, X. Fléchard, B. Pons, E. Liénard, G. Ban, M. Breitenfeldt, C. Couratin, P. Delahaye, D. Durand, P. Finlay, B. Guillon, Y. Lemière, F. Mauger, A. Méry, O. Naviliat-Cuncic, T. Porobic, G. Quéméner, N. Severijns, J.-C. Thomas, Electron shakeoff following the β^+ decay of ^{19}Ne$^+$ and ^{35}Ar$^+$ trapped ions. Phys. Rev. A **97**, 023402 (2018). https://doi.org/10.1103/PhysRevA.97.023402
43. S. Van Gorp, M. Breitenfeldt, M. Tandecki, M. Beck, P. Finlay, P. Friedag, F. Glück, A. Herlert, V. Kozlov, T. Porobic, G. Soti, E. Traykov, F. Wauters, C. Weinheimer, D. Zákoucký, N. Severijns, First $\beta - \nu$ correlation measurement from the recoil-energy spectrum of penning trapped ^{35}Ar ions. Phys. Rev. C **90**, 025502 (2014). https://doi.org/10.1103/PhysRevC.90.025502
44. M.T. Hassan, W.A. Byron, G. Darius, C. DeAngelis, F.E. Wietfeldt, B. Collett, G.L. Jones, A. Komives, G. Noid, E.J. Stephenson, F. Bateman, M.S. Dewey, T.R. Gentile, M.P. Mendenhall, J.S. Nico, Measurement of the neutron decay electron-antineutrino angular correlation by the aCORN experiment. Phys. Rev. C **103**, 045502 (2021). https://doi.org/10.1103/PhysRevC.103.045502
45. F.M. Gonzalez, E.M. Fries, C. Cude-Woods, T. Bailey, M. Blatnik, L.J. Broussard, N.B. Callahan, J.H. Choi, S.M. Clayton, S.A. Currie, M. Dawid, E.B. Dees, B.W. Filippone, W. Fox, P. Geltenbort, E. George, L. Hayen, K.P. Hickerson, M.A. Hoffbauer, K. Hoffman, A.T. Holley, T.M. Ito, A. Komives, C.-Y. Liu, M. Makela, C.L. Morris, R. Musedinovic, C. O'Shaughnessy, R.W. Pattie, J. Ramsey, D.J. Salvat, A. Saunders, E.I. Sharapov, S. Slutsky, V. Su, X. Sun, C. Swank, Z. Tang, W. Uhrich, J. Vanderwerp, P. Walstrom, Z. Wang, W. Wei, A.R. Young, Improved neutron lifetime measurement with UCNτ. Phys. Rev. Lett. **127**, 162501 (2021). https://doi.org/10.1103/PhysRevLett.127.162501
46. B.R. Holstein, S.B. Treiman, Tests of spontaneous left-right-symmetry breaking. Phys. Rev. D **16**, 2369–2372 (1977). https://doi.org/10.1103/PhysRevD.16.2369
47. D. Melconian, J.A. Behr, D. Ashery, O. Aviv, P.G. Bricault, M. Dombsky, S. Fostner, A. Gorelov, S. Gu, V. Hanemaayer, K.P. Jackson, M.R. Pearson, I. Vollrath, Measurement of the neutrino asymmetry in the β decay of laser-cooled, polarized ^{37}K. Phys. Lett. B **649**(5), 370–375 (2007). https://doi.org/10.1016/j.physletb.2007.04.047
48. P.A. Vetter, J.R. Abo-Shaeer, S.J. Freedman, R. Maruyama, Measurement of the β-ν correlation of ^{21}Na using shakeoff electrons. Phys. Rev. C **77**, 035502 (2008). https://doi.org/10.1103/PhysRevC.77.035502
49. S. Vanlangendonck, N. Severijns, L. Hayen, F. Glück, Influence of the recoil-order and radiative correction on the β decay correlation coefficients in mirror decays. Phys. Rev. C **106**, 015506 (2022). https://doi.org/10.1103/PhysRevC.106.015506
50. A. Falkowski, M. González-Alonso, A. Palavrić, A. Rodríguez-Sánchez, Constraints on subleading interactions in beta decay Lagrangian. (2021). arXiv:2112.07688
51. V. Araujo-Escalona et al., Simultaneous measurements of the β-neutrino angular correlation in ^{32}Ar pure Fermi and pure Gamow-Teller transitions using β-proton coincidences. Phys. Rev. C **101**, 055501 (2020). https://doi.org/10.1103/PhysRevC.101.055501
52. O. Naviliat-Cuncic, Searches for exotic interactions in nuclear beta decay. AIP Conf. Proc. **1753**, 060001 (2016). https://doi.org/10.1063/1.4955362