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Limits to second-class nucleonic and mesonic currents

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Abstract. Second-class currents, i.e those of irregular G-parity in the definition of Weinberg, induce differences between the ft-values for positive and negative electron emission in the mirror beta-decay of complex nuclei and, together with weak magnetism, there affect various correlation phenomena. Such currents might arise either from (strong-interaction-clad) $NNe\nu$ vertex terms or from the in-flight decay of exchange mesons, most probably $\omega \to \pi e\nu$, or from both, in the manner first explored in detail by Kubodera, Delorme and Rho. The nucleonic and mesonic effects can be (partially) disentangled only by studying a suite of cases and inter-relating those cases through suitable many-body wave-functions. Present data are analyzed to show that, at the 90% CL, the amplitudes of second-class (strong-interaction-clad)-nucleonic-vertex and meson-exchange terms are both at least an order of magnitude below those of corresponding first-class terms. These experimental upper limits are themselves about one order of magnitude larger than the values expected from m_u, m_d symmetry-breaking. Evidences from particle physics are quantitatively comparable to, and consistent with, those from nuclear structure physics but are less detailed and less surely based.

1 Introduction

1.1 Nucleonic beta-decay

Within the vector-axial paradigm of the standard model the nucleonic weak current has leading terms in g_V and g_A, belonging to the "point" nucleon, in the vector and axial parts respectively. Lorentz co-variance requires additional, momentum-transfer-dependent, terms namely those proportional to g_M (weak magnetism) and g_S (induced scalar) in the vector part and g_T (induced tensor) and g_P (induced pseudo-scalar) in the axial part. Of these four momentum-transfer-dependent terms, all induced by the hadronic cladding of the primitive "point" nucleon, two, namely those in g_M and g_P, are termed first class [1] in that their signs follow those of the leading terms in their respective currents under the transformation $n \leftrightarrow p$; they figure in the standard model. The other two momentum-transfer-dependent terms, namely those in g_S and g_T, are termed second class [1] in that their signs change relative to those of their respective leading terms under $n \leftrightarrow p$; they do not figure in the standard model. This immediately gives the somewhat counter-intuitive expectation that, most generally, although not within the standard model, mirror allowed beta-decay transitions do not have the same ft-values *e.g.* the mirror decays of ^{12}B and ^{12}N to the ground state of ^{12}C do not go at the same intrinsic rate.

Specifically, for an on-shell nucleon of initial and final momenta p_i and p_f respectively, we have, in a usual notation and convention:

$$\langle p_f|V_\mu|p_i\rangle = i\overline{u}(p_f)\{g_V\gamma_\mu + g_M\sigma_{\mu\nu}q_\nu + ig_Sq_\mu\}u(p_i); \quad (1)$$
$$\langle p_f|A_\mu|p_i\rangle = i\overline{u}(p_f)\{g_A\gamma_\mu + g_T\sigma_{\mu\nu}q_\nu + ig_Pq_\mu\}\gamma_5u(p_i). \quad (2)$$

Most generally, one classifies the elements ΔJ_μ of the hadronic weak current $J_\mu = V_\mu + A_\mu$ in terms of their behaviour, $\Delta J_\mu = \pm G\Delta J_\mu G^{-1}$, under the G-parity operation $G = CU$ where C is the charge-conjugation operator and U is the charge-symmetry operator $U = e^{i\pi T_2}$. This full definition is necessary if mesons figure explicitly in the initial and/or final states of the weakly-transforming system but if they do not, and even if they figure microscopically in the internal description of those hadronic states, as they might, for example, in nuclear beta-decay, charge conjugation need not be invoked and we may make the classification just in terms of U: $\Delta J_\mu = \pm U\Delta J_\mu U^{-1}$. This permits us, for example, to relate the beta-decay of ^{12}B by e^--emission directly to that of ^{12}N by e^+-emission to the same final state rather than by, as would be the case using the full G-parity operation, relating the decay

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of ^{12}B by e^--emission to that of anti-^{12}N by e^--emission thence, under CPT, to that of ^{12}N by e^+-emission. However, although the full G-parity is not needed to classify nuclear beta-decay just with reference to its initial and final states, whether or not we recognize the involvement of exchange mesons *internal* to the nuclei, we will here continue to use that language to facilitate discussion of such internal mesonic effects.

In the usual sign convention the leading term in the vector current (1) transforms without change of sign under the G-parity operation whereas the leading term in the axial current (2) changes sign so that if, for example, in an axial transition, the G-parity of an exchange meson changes sign as that meson makes its contribution to the overall nuclear beta-decay, by itself beta-decaying in flight between two nucleons, its contribution is first class and if it does not change sign its contribution is second class.

The first-class weak magnetism term $g_M \sigma_{\mu\nu} q_\nu$ in the weak nucleonic vector current (1) is measured by:

$$g_M = (\mu_{ap} - \mu_{an})/2M \approx 3.71/2M \approx 1.98 \times 10^{-3}\ MeV^{-1} \quad (3)$$

where μ_{ap} and μ_{an} are the anomalous magnetic moments of proton and neutron respectively and M is the nucleon mass. The corresponding, induced tensor, term $g_T \sigma_{\mu\nu} q_\nu \gamma_5$ in the axial current is second-class so it is natural to gauge the strength of possible second-class currents in nucleonic axial beta-decay by comparing g_T with g_M: this we shall do. Now, as we have remarked, g_T is zero within the standard model; non-zero values are contemplated only with considerable awkwardness although they cannot be excluded on a fundamental basis [2] and they must figure at some level, if only effectively, through mass-difference-induced symmetry-breaking as we shall note shortly.

Of the remaining induced terms: the first-class pseudoscalar $g_P q_\nu$ in the axial current is given by PCAC but its contribution goes as the mass of the associate charged lepton and, quantitatively, we need not consider it in the context of nuclear beta-decay; the induced scalar $g_S q_\nu$ in the vector current is second class but is zero by CVC: we do not question that here while recognizing that mass-difference-induced symmetry-breaking effects will give to it also a finite value at some level uninteresting for our present enquiry into nuclear beta-decay. We therefore look for second-class effects signalled by a finite value for the induced-tensor coupling constant g_T in the axial current (2).

As we have already remarked, a finite value for g_T is indeed to be expected on a symmetry-breaking basis if only because of the m_u, m_d quark mass difference. Most naively one might expect:

$$|g_T/g_M| \approx (m_d - m_u)/(m_d + m_u) \approx 0.3 \quad (4)$$

(using, illustratively, m_u, m_d-values from the middle of their presently-stated ranges [3]). However, this expectation would not be proper because although the quarks are the primary transforming entities in beta-decay the neutron and proton are the *effective* transforming entities and we might more reasonably expect [4]:

$$|g_T/g_M| \approx \Delta M/2M \approx 7 \times 10^{-4} \quad (5)$$

where ΔM is the neutron-proton mass difference.

An early estimate based on the dynamics of relativistic current quarks [5] gave:

$$g_T \approx (m_d - m_u)/2M\omega \quad (6)$$

where ω is a single-quark energy of about 400 MeV (for an MIT bag of $R \approx (200\ \text{MeV})^{-1}$) so that we might then expect $g_T \approx 4 \times 10^{-6}\ \text{MeV}^{-1}$. More-reliable estimates of g_T derive from the application of QCD sum rules to m_u, m_d symmetry-breaking which yields [6] (using $m_u = (5.1 \pm 0.9)$ MeV; $m_d = (9.0 \pm 1.6)$ MeV):

$$|g_T/g_M| = 0.0052 \pm 0.0018 \quad (7)$$

i.e.:

$$g_T = (1.0 \pm 0.4) \times 10^{-5}\text{MeV}^{-1} \quad (8)$$

Symmetry-breaking estimates of g_T are proportional to $m_d - m_u$ for which the ostensibly-accurate value of 6.14 ± 0.36 MeV has been more recently quoted in association with an analysis of ρ^o-ω mixing [7]. This would lead to an estimate of g_T about 60% larger than that of (8).

Any definite experimental signal in excess of $g_T \approx (1-2) \times 10^{-5}\ \text{MeV}^{-1}$ would therefore be an indication of possible new physics but an upper limit greater than this would not impugn the standard model.

Interesting semantic questions are raised by these discussions of symmetry-breaking and the induced terms. Distinction is sometimes drawn between "real" and "apparent" effects. Thus, in the vector current, because different masses are inevitably involved for initial and final states, CVC will be *ipso facto* eroded giving the *operational* appearance of a finite value for g_S; the formal rôles of the g_V and g_S of (1) become to some small measure merged so that the second-class niche occupied by g_S acquires some "contamination" by the first-class g_V (see *e.g.* [8]). It is then correct to argue that the second-class current associated with the g_S of (1) does not "really" exist but is an illusion due to a structural defect namely the subversion of isospin by mass differences. We may recall the familiar example of super-allowed vector transitions in nuclei within isospin multiplets. These take place at a rate some 1% less than expected from CVC. We could therefore say that CVC has been broken by 1% by the mass differences between the members of the isomultiplet. We do not, however, say this because we prefer to express the situation in terms of the breaking of the (*nuclear*) symmetry of the isomultiplet which has the easily-understandable effect of lowering the square of the nuclear matrix element by 1% leaving the fundamental (*nucleonic*) CVC symmetry intact (although itself prey to subversion by neutron-proton, *i.e.* quark, mass differences). We put it this way because we understand the structural defects from which complex nuclei suffer on account of departures from perfect charge-independence of their internal constitution and the effect that those defects have upon the beta transition rate due to the (almost)-perfectly-CVC-respecting nucleonic weak interaction. So also in the case of particles we might be able to understand operationally second-class terms and, concomitantly, the departure from their standard values of the first-class terms, by reference to symmetry-breaking structural defects due to quark mass differences etc. without reference to any "fundamental" finite g_S and g_T. However, we do not yet know enough about particle structure and non-perturbative QCD to embark whole-heartedly along this route, although we have noted a significant beginning [6], and so we lump our ignorance into an operational g_S and an operational g_T.

1.2 Exchange currents: the KDR model

We have so far, in (1) and (2), considered only second-class effects associated with the isolated but strong-interaction-clad $NNe\nu$ vertex of free-nucleon decay. But since our immediate concern is with the beta-decay of the complex nucleus as a whole any experimental second-class signal will stem not only from the strong-interaction-clad $NNe\nu$ vertex but also from any effect deriving from nucleon exchange currents; the nuclear context then also requires that off-mass-shell effects, including $N\overline{N}$ terms, be explicitly reckoned with [9,10]. In the following we largely follow [10] (call this the KDR model) and consider the most-likely direct mesonic source of a second-class current to be $\omega \to \pi e\nu$ since the ωNN coupling constant is large and the ω is the lightest meson of appropriate quantum numbers, the ω being emitted by one nucleon and the π being absorbed by another, the $\omega \to \pi e\nu$ decay taking place "in the air" between the two nucleons. (We must also recognize that the π might be absorbed by the same nucleon that emitted the ω this process then constituting an element, or perhaps even the whole, of the $NNe\nu$ vertex g_T.) This $\omega \to \pi e\nu$ process is second-class because ω and π are of the same G-parity while, as we have noted, the G-parity associated with the leading term changes in the axial weak hadronic current (2) with which we are presently concerned. Of course, the KDR model need not be specific to the ω-meson as the responsible agency of second-class exchange: any meson, or combination of mesons, of appropriate quantum numbers might be involved.

In a complex nucleus nucleons are off-shell and this demands that the original strong-interaction-clad $NNe\nu$ term for a free nucleon associated with the induced tensor take, in the simplest non-trivial formulation, the expanded form:

$$i(g_T \sigma_{\mu\nu} q_\nu \gamma_5 + i g'_T P_\mu \gamma_5) \tag{9}$$

the second term being associated with an exchange-pion-induced $N\overline{N}$-pair and the q and P referring, respectively, to the difference and the sum of the initial and final nucleon four-momenta. (Call (9) the expanded $NNe\nu$ vertex term.)

This leads us to define the constant:

$$\zeta = g_T + g'_T. \tag{10}$$

The $\omega \to \pi e\nu$ exchange term is measured by a form factor F_ω which, together with the reasonable assumption that the pion is "soft" [11] leads to the exchange-related constant:

$$\lambda = \frac{m_\pi^3 g_{\pi NN}^2}{24\pi M^2}\left(g'_T - \frac{g_{\omega NN} F_\omega}{g_{\pi NN} m_\omega^2}\right). \tag{11}$$

All second-class observables may now be expressed through combinations of ζ and λ; it is important to stress that they **must** *be; no single experiment on a single mirror decay process can give information on g_T.*

1.3 Experimental searches

There are, broadly speaking, two chief modes possible for search for second-class currents in complex nuclei. The first mode considers mirror axial beta-decay and defines the asymmetry:

$$\delta = (ft)^+/(ft)^- - 1 \tag{12}$$

where $(ft)^+$ and $(ft)^-$ refer to the positive and negative electron emitters respectively. In the simplest (impulse approximation) picture [12], which does not include any meson-related or off-shell effects, δ is non-zero if g_T, here a pure strong-interaction-clad $NNe\nu$ vertex term, is non-zero because the effect of g_T, being second-class, by definition adds to that of g_A on one side of the mirror and subtracts from it on the other and we have [12]:

$$\delta = -\frac{4}{3}\frac{g_T}{g_A} W \tag{13}$$

where $W = W_0^+ + W_0^-$, W_0^+ and W_0^- being, respectively, the total end-point energies of the positive and negative electron mirror decays. (We expect proportionality of δ to W on account of the proportionality to q_ν of the g_T term in (2): the induced tensor is second-forbidden in nuclear-structure parlance; we consider only decays that are axial and allowed over-all *i.e.* those of $\Delta \boldsymbol{J} = 1$ without change of parity.) But, as we have seen, this impulse-approximation picture is incomplete and we must also reckon with the off-shell-related g'_T and with $\omega \to \pi e\nu$ exchange, the former figuring in (10) and the two figuring together in (11). This has the effect of replacing (13) by [10]:

$$\delta = -4\lambda J/g_A + \frac{4}{3}\left(\frac{1}{2}\lambda L - \zeta\right) W/g_A \tag{14}$$

where J and L are nuclear-structure-dependent ratios of 2-body to 1-body matrix elements. In the impulse approximation J and L fall away, ζ reduces to g_T and (14) reduces to (13).

An important special case of this $(ft)^\pm$-approach is afforded by the comparison of ^{8}Li and ^{8}B decay. These bodies decay to the broad $J^\pi = 2^+$ continuum that incorporates the first-excited state of ^{8}Be nominally at about 3 MeV and this permits a differential determination of δ as a function of excitation within ^{8}Be, hence of the summed energy release W. This special case requires special treatment beyond (14); it will be considered in detail later.

The second mode of search involves the comparison of beta-particle-energy-dependent correlations between nuclear spin and direction of electron emission from the two sides of the mirror or between the direction of emission of the electrons and of some subsequent radiation. This determines a combination of a second-class signal measured by

$$\kappa = \zeta + \lambda L \tag{15}$$

and an element due to the first-class weak magnetism which must be separately assessed to extract the second-class effect. We must assume that this separation of first-class and second-class effects can be confidently performed following "strong" CVC provided that the relevant electromagnetic information is experimentally available with adequate precision.

1.4 Nuclear structure and the suite of data

We have already stressed that both in the $(ft)^{\pm}$-approach and in the correlation approach the experimental signal involves both ζ and λ hence both the expanded, and so exchange-related, strong-interaction-clad $NNe\nu$ vertex term and the $\omega \to \pi e\nu$ exchange term that we are taking to be the chief explicit mesonic factor in the second-class effect and that *these ζ and λ contributions cannot be separated in a single experiment on a single pair of mirror transitions. A null result in a single experiment tells us nothing about the strength of second-class currents in general* because, as we see from (14) and (15) the various nucleonic and mesonic contributions might conspire to zero although individual second-class terms might be large. It is therefore *essential*, in placing a meaningful limit on second-class currents in general, to have available a suite of experimental data derived from a range of mirror transitions and to analyze it as a *suite* to separate out and separately to assess the ζ and λ elements. That is the chief purpose of the present paper.

It is evident that our analysis depends upon J and L, the ratios of 2-body to 1-body matrix elements, the determination of which demands commitment to specific many-body wave-functions for the nuclei involved. Such wave-functions are also necessary for removing the effects of any forbidden transitions not relevant for the present analysis. Now, excellent many-body wave-functions are available for all the bodies of concern in our present study but, unfortunately, no extraction of J and L from them has yet been made so we must continue to use the values following [10] and [13] as quoted in [14]; these are probably reasonably reliable in the light nuclei of present concern but values from modern wave-functions would be very welcome.

An important element of our present uncertainty in the evaluation of J and L concerns the importance of short-range NN correlations within the many-body wave-functions. The effect of these, supplementing the wave-functions of [10] and [13] might be quite considerable [14] but it is at present rather uncertain; its confident evaluation must await the application of the modern many-body wave-functions to which reference has just been made. We do not attempt to take short-range correlations into account here in our primary analysis but will report below on their effect as estimated following [14]. This consideration re-emphasizes the high desirability of a critical modern analysis of the entire wave-function-dependent package: in that sense our present analysis is quantitatively-illustrative rather than definitive.

1.5 Charge-dependence of the nuclear structure

A further uncertainty that plagues our analysis relates to another aspect of the many-body wave-functions that must be used: their respect, or otherwise, of the charge-dependence of the NN force including the Coulomb interaction. In both the $(ft)^{\pm}$-approach and in the use of correlations we are concerned with comparing effects from the two sides of an isospin mirror. But that mirror is not true: the various charge-dependencies distort the reflection so that the T_3 and $-T_3$ bodies involved in the decays differ in structure to some degree and this mimics the effect of a second-class current in, for example, making $(ft)^+ \neq (ft)^-$ even in the total absence of a second-class current. This problem has long been recognized and studied in detail [15]; it, rather than experimental precision, limits the sharpness with which we can confidently extract information as to ζ and λ from $(ft)^{\pm}$-comparison. This same problem also afflicts the correlation approach although its importance there was, despite warnings [16], long underestimated on the grounds that there the leading, i.e. g_A-proportional, term in the allowed component of the transition gives no signal; the considerable *de facto* importance of such correction in correlation experiments has, however, now been recognized and is, there also, beginning seriously to limit the confidence with which a second-class effect can be assessed [17].

2 The data base

2.1 $(ft)^{\pm}$-values

Systematic search for second-class current effects began in 1970 [18] when it appeared that large values of the $(ft)^{\pm}$-asymmetry δ of (12) were found in many light-nuclear systems. However, these values spread widely, were of either sign and were not systematically related through a δ such as that of (13) as was, at that time, to be expected [12]. Subsequent experimental re-examination of many of the cases brought better order into the ensemble [19] in a manner not inconsistent, superficially, with $g_T \approx g_M$ i.e. with equal strength for second-class and first-class currents. However, at the same time [15], evaluation of the effect upon δ of binding-energy differences across the flawed $\pm T_3$ mirror showed that the observed $(ft)^{\pm}$-asymmetries could well have that trivial origin.

After correction for these binding-energy differences the ensemble of $(ft)^{\pm}$-asymmetry defines the ellipse in the ζ, λ-plane shown in Fig. 1. (In constructing this ellipse,

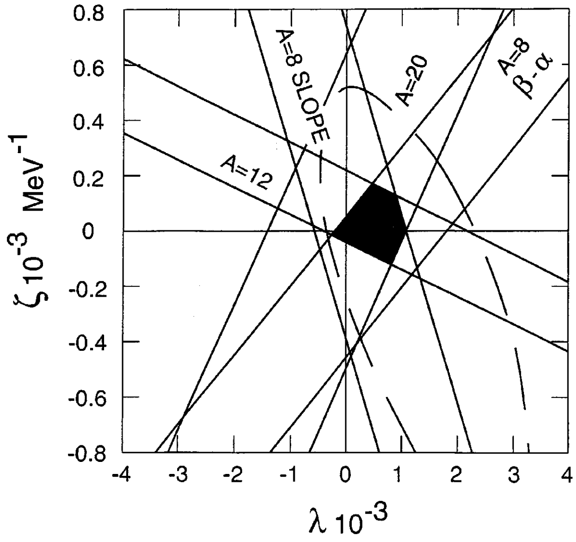

Fig. 1. One-standard-deviation limits on the Kubodera, Delorme and Rho second-class parameters ζ and λ from the individual experimental approaches indicated on the bands and from the ensemble of data on $(ft)^{\pm}$-values indicated by the ellipse. The filled area is common to all data. The resulting 90% CL values are: $\zeta = (0.04 \pm 0.18) \times 10^{-3}$ MeV^{-1}; $\lambda = (0.5 \pm 0.9) \times 10^{-3}$

slightly up-dated from that in [16] following more recent experimental information, only data from $T = 1$ decays to a unique $T = 0$ final state have been used. $T = \frac{3}{2}$ decays to mirror $T = \frac{1}{2}$ final states are unreliable for present analysis [16] owing to strong binding-energy asymmetries as between the $T_3 = \pm\frac{1}{2}$ final states.)

The ellipse of Fig. 1 gives evidence for second-class currents neither through the expanded $NNe\nu$ vertex term ζ nor through the exchange-related term λ but the limits are not very tight, that on ζ corresponding, at 90% CL, to no better than about 30% of the g_M of weak magnetism.

2.1.1 The $A = 8$ system

Reference has already been made to the possibility presented by the $A = 8$ system of, in effect, investigating the $(ft)^{\pm}$-relationship as a function of the summed energy release W of (14) i.e of excitation energy within the daughter nucleus ^{8}Be. Experiment [20] showed no sign of any significant change of the δ of (12) over a range of excitation of about 7.5 MeV in ^{8}Be corresponding to a range of 15 to 30 MeV for W, certainly not the proportionality of δ to W naively to be expected from (13), although δ itself was everywhere quite large, viz. about 0.1.

The best estimate for the δ-value due to the binding-energy effect alone was about 0.08 [15] so no significant overall second-class current effect could be claimed since the estimate of the binding-energy effect is itself significantly sensitive to details such as the choice of the effective optical model potential for the generation of the single-particle wave-functions and the relevant parentage structures of the initial and final states. It is, however, still necessary to examine these "$A = 8$ slope" results in the light of the KDR ζ, λ-model. This is not straightforward [21] and is complicated by the fact that the profile of ^{8}Be as seen by its feeding through ^{8}Li, ^{8}Be beta-decay is significantly different, particularly at high excitation energy in ^{8}Be, from the profile seen through the gamma-decay of the state in ^{8}Be analogue to the ground states of ^{8}Li and ^{8}B [22,23]. (This analogue state in ^{8}Be is actually dissolved into a mixed $T = 0 + T = 1$ close doublet but that involves only little complication.) The quantitative explanation for this strikingly-different feeding of the continuum of ^{8}Be through the beta and gamma channels is yet to be determined: whether in terms of over-lapping states in ^{8}Be [24] or of some excitation-dependent constitution of the very broad "first excited state of ^{8}Be" in question.

It was pointed out [25] that the predominant {431} space symmetry of the initial ^{8}Li and ^{8}B beta-decaying states cannot be changed by the axial operator and that the predominant space symmetry of the broad ^{8}Be state is {44} so that the beta-transitions go only to a small admixture of {431} into the broad state (as witness their quite large $\log ft$ values of about 5.6). If we take the view that the wave-function of the broad ^{8}Be state is not a proper eigenfunction but can have a make-up that is a function of excitation then we may imagine that the {431} component of the wave-function may be introduced perturbatively by mixture with a general $J^{\pi} = 2^+$; $T = 0$ condition of ^{8}Be at higher excitation that need not be specified in detail so that the ratio of {431} to {44} amplitudes in the broad state will increase as we go towards higher excitation, i.e. nearer to the {431} source. However, the {431} $T = 1$ analogue(s) in ^{8}Be of the ^{8}Li and ^{8}B beta-decaying ground states can link by the space part of the $M1$ operator to the dominant {44} component of the broad ^{8}Be state (as witness the healthy $M1$ $|M|^2$-value of rather more than 0.1 in Weisskopf units) as well as, through the spin part, to the smaller {431} component so that the axial operator will be progressively favoured, relative to the $M1$ operator, as we go to higher excitations in ^{8}Be, qualitatively explaining the differing profiles of the final "state" as seen through beta-decay and through gamma-decay.

It is evident that we do not, at present, have a sufficient quantitative understanding of this situation in ^{8}Be, in particular the excitation-dependence effective for J and L, to do other than take these as constants appropriate to the nominal $J^{\pi} = 2^+$ first-excited state, analyzing the experimental data using the modification of (14) appropriate for this case ((6) of [13]) and using the J;L-values from [13] which we shall do throughout the rest of this paper. Some justification for this derives from the fact that when the experimental excitation-energy-independent results for δ are corrected for the binding-energy effect, using J;L-values appropriate for the nominal $J^{\pi} = 2^+$ first-excited final state of ^{8}Be, they remain excitation-energy-independent [16] which they would not do if the effective wave-function for ^{8}Be were itself significantly energy-dependent.

This defines the band labelled "$A = 8$ slope" in Fig. 1 [13]. We recognize that further analysis will be desirable as our understanding of the wave-function situation in ^{8}Be improves.

2.2 Correlation experiments

Important constraint comes from experiments involving beta-energy-dependent correlations with aligned or polarized nuclei or with subsequent radiations.

2.2.1 $A = 8$

Energy-dependent correlations between the beta-particles emitted in ^{8}Li,^{8}B-decay and the alpha-particles from the subsequent break-up of the ^{8}Be [26] combined with information from the radiative decay of the close doublet analogue state(s) in ^{8}Be [23] yield [23], in the notation of Holstein [27]:

$$d_{II}/Ac = 0.0 \pm 0.3 \pm 0.3 \quad (16)$$

and:

$$d_{II}/Ac = -(0.5 \pm 0.2 \pm 0.3) \quad (17)$$

from the 1975 and 1980 experiments of [26] respectively where, in the notation of the present paper:

$$d_{II}/Ac = 2M\kappa/g_A. \quad (18)$$

These results are also subject to the strictures concerning the uncertain situation in ^{8}Be that we have just exposed. In the present case, however, the impact of those strictures is not so severe since the correlation experiments are dominated by the lower excitations in ^{8}Be where we may more confidently speak of a final state well-defined in wave-function terms.

At this point it is necessary to determine how to handle errors when they are of more than one type, statistical and systematic, such as given in (16) and (17). Our present objective is to set (conservative) limits on the possible strengths of second-class currents, rather than to determine actual significant values, so it is appropriate, as standard in such circumstances, to combine errors of different type by linear addition rather than by quadrature. Doing this and combining the results of (16) and (17) we find:

$$\kappa = -(0.20 \pm 0.25) \times 10^{-3}\ \text{MeV}^{-1} \quad (19)$$

This value defines the band in Fig. 1 labelled "$A = 8\ \beta - \alpha$".

2.2.2 $A = 12$

There have been several experiments involving beta-particle-energy-dependent correlations with aligned or polarized ^{12}B,^{12}N decaying to the ground state of ^{12}C. These yield:

$$\kappa = (0.20 \pm 0.47) \times 10^{-3}\ \text{MeV}^{-1}\ [28] \quad (20)$$

$$\kappa = -(0.09 \pm 0.32) \times 10^{-3}\ \text{MeV}^{-1}\ [29] \quad (21)$$

$$\kappa = -(0.14 \pm 0.42) \times 10^{-3}\ \text{MeV}^{-1}\ [30] \quad (22)$$

$$\kappa = (0.15 \pm 0.17) \times 10^{-3}\ \text{MeV}^{-1}\ [17] \quad (23)$$

Combining these date yields:

$$\kappa = (0.08 \pm 0.14) \times 10^{-3}\ \text{MeV}^{-1} \quad (24)$$

and the band in Fig. 1 labelled "$A = 12$".

2.2.3 $A = 20$

Beta-particle-energy-dependent/gamma-ray directional correlations in the $A = 20$ system involving the first-excited state of ^{20}Ne in the decay of ^{20}F and ^{20}Na [31] yield:

$$\kappa = (0.16 \pm 0.51) \times 10^{-3}\ \text{MeV}^{-1} \quad (25)$$

This value defines the band in Fig. 1 labelled "$A = 20$"

2.2.4 Binding energy corrections

It should be remarked that some of the results displayed as the bands in Fig. 1 have been corrected for nuclear-structure-dependent binding energy effects and some have not. The possible seriousness of such notoriously-tricky corrections may be judged from the estimate in [17] where the correction amounts to approximately one half of the stated experimental error; corrections in most other cases would be considerably less relative to their errors. Were such corrections not made in [17] (23) above would read: $\kappa = (0.08 \pm 0.13) \times 10^{-3}$ MeV^{-1} and (24) would read: $\kappa = (0.05 \pm 0.11) \times 10^{-3}$ MeV^{-1} which would bring no significant change to our conclusions.

2.3 Limits to ζ and λ

The filled area of Fig. 1 is common to all the data there represented,(Note that if, following the above discussion, the "$A = 8$ slope" data were, unjustifiably, to be completely discounted it would have very little effect upon the filled area and so upon our subsequent conclusions.) Further data from other experiments of lower accuracy in other systems are available but do not affect the present discussion.

By simultaneous analysis of the results displayed in Fig. 1 we derive, at 90% CL:

$$\zeta = (0.04 \pm 0.18) \times 10^{-3}\ \text{MeV}^{-1} \quad (26)$$

$$\lambda = (0.5 \pm 0.9) \times 10^{-3} \quad (27)$$

As remarked above, this analysis has been carried out, following [10,13,14], using J,L-values evaluated without explicit regard for short-range correlations in the nuclear many-body wave-functions. Repeating the entire analysis with the inclusion of short-range correlations as estimated in [14] yields a ζ-value identical to that of (26) and a λ-value of $(0.6 \pm 1.4) \times 10^{-3}$ i.e. little changed from that of (27). In the following we use the values given in (26) and (27).

We immediately note that the 90% CL of 0.22×10^{-3} MeV^{-1} on $|\zeta|$ is just about one tenth of the value of g_W given in (3) viz. 1.98×10^{-3} MeV^{-1} which establishes the fact that the second-class term in the nucleonic axial current, as defined through ζ, is substantially weaker than the corresponding term in the vector current, *a result that could not have been arrived at without consideration of a* **suite** *of data such as that analyzed here.*

This upper limit for the second-class nucleonic effect is approximately one order of magnitude greater than the figure suggested by (8) as to be expected from m_u,m_d symmetry-breaking. This is a gauge of how close we may be in these *nuclear* structure studies to becoming sensitive to *nucleon* structure.

We also see from Fig. 1 and from (27) that there is no suggestion of a second-class mesonic effect, specifically $\omega \to \pi e\nu$, such as might give a significant value for λ. We gain a *impressionistic* estimate of a limit to the strength of the second-class $\omega \to \pi e\nu$ by setting g'_T equal to zero in (11) and extracting F_ω from λ. (Note that this heuristic procedure is equivalent to the assumption that the putative second-class current is not conserved since such *Ansatz* of conservation would imply $\lambda = 0$ or $g'_T = g_{\omega NN}F_\omega/g_{\pi NN}m_\omega^2$ from (11) hence $F_\omega = 0$ if $g'_T = 0$.)

This procedure is equivalent to deriving an effective second-class $g_{T\omega}$ from (11), associated with $\omega \to \pi e\nu$, that we may compare with the first-class g_M of (3) to assess the strength of the second-class relative to the related first-class induced current. We now have:

$$g_{T\omega} = \frac{24\pi M^2\lambda}{m_\pi^3 g_{\pi NN}^2} \tag{28}$$

that we may compare with the first-class g_M of (3) gaining:

$$g_{T\omega}/g_M = \frac{48\pi M^3\lambda}{m_\pi^3 g_{\pi NN}^2(\mu_{ap} - \mu_{an})} \tag{29}$$

as a measure of the reduction of second-class relative to first-class current strength in the mesonic sector. Putting numerical values into (29) (using $g_{\pi NN} = 14$) and the 90% CL on $|\lambda|$ from (27), viz. 1.4×10^{-3}, we find, at 90% CL:

$$g_{T\omega}/g_M < 0.09 \tag{30}$$

suggesting that the inhibition by G-parity conservation in the mesonic beta-decay $\omega \to \pi e\nu$ is roughly comparable to that which, through ζ, we have seen for nucleonic beta-decay.

We may, alternatively, compare the F_ω of our present discussion with the corresponding quantity, F_ρ, that involves the rate of the allowed $\rho \to \pi e\nu$, as might be encouraged by their relationship within the SU(3) classification, asking for their relative impact upon their respective exchange contributions. We have [10]:

$$F_\rho = \frac{g_{\pi NN}m_\rho^2}{2g_{\rho NN}Mg_A} \tag{31}$$

so that we gain another estimate of the effect of G-parity conservation in inhibiting the amplitude of $\omega \to \pi e\nu$ of, setting $m_\omega = m_\rho$:

$$F_\omega/F_\rho = \frac{48\pi M^3 g_{\rho NN}g_A\lambda}{m_\pi^3 g_{\pi NN}^2 g_{\omega NN}}. \tag{32}$$

Putting numerical values into (32) (using additionally $g_{\omega NN} = 7$; $g_{\rho NN} = 0.6$) with the above 90% CL on $|\lambda|$ we find:

$$F_\omega/F_\rho < 0.04. \tag{33}$$

These limits have all involved, or have involved assumptions about, the off-shell g'_T. We may eliminate g'_T as between (10) and (11) to extract the composite second-class on-shell quantity:

$$\text{“}g_T\text{”} = g_T + \frac{g_{\omega NN}F_\omega}{g_{\pi NN}m_\omega^2} = (0.03\pm0.13)\times10^{-3}\ \mathrm{MeV}^{-1} \tag{34}$$

so that, at 90% CL:

$$\text{“}g_T\text{”}/g_M < 0.12 \tag{35}$$

All these rough estimates of the impact of G-parity conservation in the mesonic sector suggest that it is worth at least an order of magnitude in amplitude i.e. roughly the same as we saw for the nucleonic sector. These effective limits on F_ω correspond to a partial lifetime for the free decay $\omega \to \pi e\nu$ of greater than 10^{-7} sec, or so, i.e. a branch of less than about 10^{-15} in overall ω-decay (which has $\Gamma = 8.4$ MeV.)

Of course, we cannot cleanly separate intrinsically "nucleonic" and "mesonic" second-class effects such as $\omega \to \pi e\nu$: the latter would, if present, manifest itself not only as an exchange term, as we have considered it here, but also by effectively generating a component, or the whole, of g_T and g'_T by renormalization of the $NNe\nu$ vertices. This emphasizes the roughness of our setting $g'_T = 0$ at the same time as seeking a limit for $\omega \to \pi e\nu$.

3 Evidences from particle physics

It is of interest to compare these nuclear-structure limits on second-class currents with those deriving from the particle field.

3.1 $\tau \to \omega\pi\nu$

The decay $\tau^- \to \omega\pi^-\nu$ involves the ω of $J^\pi;T^G = 1^-;0^+$ and the π of $J^\pi;T^G = 0^-;1^-$. The decay can yield final hadronic $\omega\pi$-states of overall $J^\pi = 1^-$ in a first-class vector decay or of overall $J^\pi = 1^+$ or $J^\pi = 0^+$ in second-class axial or vector transitions respectively, the first-class and second-class effects being distinguishable by angular-distribution analysis. Experiment yields branching fractions for $\tau \to \omega\pi\nu$ of $0.0195 \pm 0.0007 \pm 0.0011$ [32] and $0.0191 \pm 0.0007 \pm 0.0006$ [33] against the CVC expectation for the first-class decay of 0.0179 ± 0.0014 [34]. These figures correspond to a 95% CL of a little over 20% on a relative second-class contribution. A slightly sharper 95% CL of 8.6% derives from a study of the angular relationships in the decay [33]. This process does not, therefore, set a limit of better than about 30% on the magnitude of the second-class relative to the first-class coupling amplitude.

3.2 $\tau \to \eta\pi\nu$

The decay $\tau^- \to \eta\pi^-\nu$ is forbidden by G-parity conservation since the η is $J^\pi;T^G = 0^-;0^+$. The limit on this branch in τ-decay is 1.4×10^{-4} at 95% CL [35]. Here we have no obvious point of first-class comparison as we had for $\tau \to \omega\pi\nu$ but we may note that the branching fractions for the G-parity-allowed cases $\tau \to \eta 2\pi\nu$ and $\tau \to \eta 3\pi\nu$ are about 1.8×10^{-3} and 5×10^{-4} respectively [3] so that "adding another pion" reduces the branching fraction by a factor of about 4. We also note that the branching fractions for $\tau \to 3\pi\nu$, $4\pi\nu$, $5\pi\nu$ and $6\pi\nu$ are about 0.09, 0.04, 0.005, and 0.0003 respectively [3] again suggesting that "adding another pion" gives a decrease in the intrinsic branching probability of order 4 allowing for decrease of phase space. We may therefore, if extremely crudely, guess that a "G-parity-allowed" branch for $\tau^- \to$ "η"$\pi^-\nu$ might have had a strength of about $4 \times 1.8 \times 10^{-3}$ with which we might compare the $\tau \to \eta\pi\nu$ limit of about 50 times less. We might then say that the upper limit on the magnitude of the relevant second-class coupling constant is somewhat less than 10 times less than that of the allowed but it must be freely admitted that this is little better than an informed guess.

This crude limit for the second-class coupling of a factor of about 10 below the allowed first-class coupling amplitude is just about the same as we have derived from our study of complex nuclei by comparison of (8) and (26) although the quantification from complex nuclei is much the surer.

It is also interesting to note that an estimate of this $\eta\pi\nu$ branching ratio in τ-decay, based upon isospin breaking in chiral perturbation theory stemming from the m_u,m_d mass difference plus a QCD sum rule analysis for the vector meson decay constant F_{a_0}, is about 1.2×10^{-5} [36]. This also suggests that experiment may be only one order of magnitude away from detecting a second-class signal in τ-decay just as we have seen it to be in nuclear beta-decay [6].

3.3 $\overline{\nu}_\mu p \to \mu^+ n$

Second-class effects would influence $\overline{\nu}_\mu p \to \mu^+ n$ and have been sought there [37]. A major problem in the quantitative analysis is the value of the mass term to be used in the second-class form factor. The experiments [37] were carried out using anti-neutrinos of up to $Q^2 \approx 1.0(\mathrm{GeV}/c)^2$ within which range the effect of the mass term in the dipole parameterization of the form factor might be quite considerable. Now, in the absence of a specific model for the second-class current we have no guidance as to the size of the mass term but if we were arbitrarily to use 1 GeV, as would be appropriate for the allowed axial coupling, we would find from the $\overline{\nu}_\mu p \to \mu^+ n$ analysis $|G_2(0)| < 0.25$ at 90% CL, where G_2 is the induced tensor form factor, to which corresponds $|g_T/g_W| < 0.15$ to compare with the $|g_T/g_W| < 0.1$ that we have presented from our nuclear structure studies. We see that, at present, the neutrino reaction does not improve our knowledge of second-class currents but is nicely complementary to it.

4 Conclusion

Studies of the beta-decay of complex nuclei set 90% confidence limits on the amplitude of second-class effects at the (strong-interaction-clad) $NNe\nu$ vertex and also in exchange currents at about 10% of the amplitude of the corresponding first-class terms. This conclusion is supported by evidence from particle studies although there the inferences are not so general and are more oblique.

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