Physics Letters B ••• (••••) •••–•••

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Probing the quenching of g_A by single and double beta decays

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ARTICLE INFO

Article history:
Received 14 May 2013
Accepted 19 June 2013
Available online xxxx
Editor: W. Haxton

Keywords:
Quasiparticle random-phase approximation
Two-neutrino double beta decays
Beta decays
Electron-capture decays
Axial-vector coupling constant

ABSTRACT

Ground-state-to-ground-state two-neutrino double beta ($2\nu\beta\beta$) decays and single beta (EC and β^-) decays are studied for the $A = 100$ (^{100}Mo–^{100}Tc–^{100}Ru), $A = 116$ (^{116}Cd–^{116}In–^{116}Sn) and $A = 128$ (^{128}Te–^{128}I–^{128}Xe) nuclear systems by using the proton–neutron quasiparticle random-phase approximation exploiting realistic effective interactions in very large single-particle bases. The aim of this exercise is to see if both the single-beta and double-beta decay observables related to the ground states of the initial, intermediate and final nuclei participant in the decays can be described simultaneously by changing the value of the axial-vector coupling constant g_A. In spite of the very different responses to single and $2\nu\beta\beta$ decays of the considered nuclear systems, the obtained results point consistently to a quenched effective value of g_A that is (slightly) different for the single and $2\nu\beta\beta$ decays.

1. Introduction

Nuclear double beta decays constitute an important issue in the present-day nuclear and neutrino physics due to their connections to many fundamental issues of particle physics. The neutrino properties are closely tied with the neutrinoless ($0\nu\beta\beta$) modes of these decays [1–3]. A massive amount of experimental effort has been, and continues to be invested to determine the corresponding half-lives in many nuclear systems. The aim is a reliable prediction of e.g. the electron–neutrino masses once the nuclear properties, in the form of nuclear matrix elements (NMEs), are under control. Unfortunately, the situation with the NMEs is still rather confusing [4,5], but definite steps forward in this respect have been taken [5]. Central issues in the calculations of the NMEs are many: (a) the effects of the chosen single-particle valence space and orbital occupancies [6–8], (b) a proper account of the shell-closure effects [5,9], (c) deformation effects [10–12] and (d) the effective value of the axial-vector coupling constant g_A of weak interactions [13,14].

In the present Letter we want to address the issue (d) of the above list of important issues of nuclear-structure calculations by using the theoretical framework of the proton–neutron quasiparticle random-phase approximation (pnQRPA) with G-matrix based nuclear forces. The issue of renormalization of g_A is a long-standing one and the renormalization is believed to derive both from truncations in the nuclear-structure calculations and from the interference of non-nucleonic, mainly Δ degrees of freedom. The renormalization stemming from the truncations in the nuclear-structure calculations has been discussed widely in the community involved in the nuclear shell-model calculations [15]. The effects of non-nucleonic degrees of freedom were examined e.g. in Ref. [16], where it was found that the Δ degrees of freedom quench g_A roughly by a factor of $\sqrt{0.6} \approx 0.77$ in the case of the Gamow–Teller (p, n) strength of nuclei.

A consistent formalism to address the renormalization problem of the matrix elements of various operators is the nuclear field theory (NFT) [17]. In the NFT there are two channels through which the renormalization can be achieved, namely (a) by renormalization of the initial and final states on the single-(quasi)particle level by a series of interactions of the P-space states (in the calculational model space) with the Q-space states (states left out of the active model space) mediated by the interaction Hamiltonian [18], and (b) by the particle–hole (two-quasiparticle) channel by involving the (collective) phonons of the system [17]. In particular, following the steps outlined in [18], i.e. including both the quasiparticle and phonon degrees of freedom in the renormalization, one finds for the renormalized matrix element

$$\langle f|M_{\mathrm{GT}}|i\rangle_{\mathrm{renormalized}} = \langle f|M_{\mathrm{GT}}|i\rangle_{\mathrm{bare}}\bigl(1 - F(\omega_{\mathrm{GT}})\bigr), \quad (1)$$

where the function $F(\omega_{\mathrm{GT}})$ reduces to the usual polarization function [17] if the energy of the giant Gamow–Teller mode is much larger than the energy difference between initial ($|i\rangle$) and final ($|f\rangle$) state. In this limit the renormalized strength of the low-energy single beta decay amounts to approximately 66 per cent of the bare value [18]. In the present context, this over-

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0370-2693/$ – see front matter
http://dx.doi.org/10.1016/j.physletb.2013.06.042

all renormalization can be included in the effective value of g_A which we try to extract by comparison with the available data.

In the case of the two-neutrino double-beta ($2\nu\beta\beta$) decay we are dealing with a perturbative expression of the NME with a separable structure, unlike in the case of the $0\nu\beta\beta$ decay where the intermediate neutrino propagator makes the NME non-separable. The separable structure means that the decay involves one nucleon at a time and the decay vertices can be separately renormalized by the above-described procedures. From this point of view the g_A of single beta and $2\nu\beta\beta$ decays renormalize in a similar fashion. However, we still leave open the question of the similar or different renormalizations of these two decay variants and discuss the renormalization of g_A without prejudices by the two methods outlined below.

For the present investigations of the effective value of g_A we have harnessed nuclear systems where both single-beta (EC and β^-) and $2\nu\beta\beta$ half-lives (see [19]) have been measured for transitions between ground states of the participant nuclei. These systems number precisely three, namely the $A = 100$ system containing the triple ^{100}Mo–^{100}Tc–^{100}Ru of nuclei, the $A = 116$ system with the triple ^{116}Cd–^{116}In–^{116}Sn and the $A = 128$ system of ^{128}Te–^{128}I–^{128}Xe nuclei. In the following we investigate how the changes in the effective value of g_A, g_A^{eff}, affect the computed $2\nu\beta\beta$ half-lives and the comparative half-lives ($\log ft$ values) of single beta decays. This study will be accomplished by resorting to the following two methods:

- Method MI: In the first method we assume that the g_A of single β and $2\nu\beta\beta$ decays renormalize in the same way. We then go through the following steps; step (i): we start from a given value of g_A^{eff}, say $g_A^{\text{eff}} = 0.8$, and then extract, by using this value of g_A^{eff}, the experimental value of the $2\nu\beta\beta$ NME, NME(2ν, exp) (the value of NME(2ν, exp) is proportional to $(g_A^{\text{eff}})^{-2}$ as shown below, in Eq. (2)). Step (ii): we fix the value of the particle–particle strength parameter g_{pp} of the pnQRPA [20] by reproducing the value of NME(2ν, exp). Step (iii): we calculate, by using this extracted value of g_{pp} and the given g_A^{eff}, the $\log ft$ values of the EC and β^- transitions corresponding to the decays from the first 1^+ state of the intermediate nucleus to the initial and final nuclei of the $2\nu\beta\beta$ decay, respectively. Step (iv): finally we compare the computed $\log ft$ values with the corresponding experimental ones to see how closely they correspond to each other. In an ideal case there would be one value of g_A^{eff} (and the corresponding g_{pp}) with which both the NME(2ν, exp) and the two $\log ft$ values can be simultaneously reproduced. Such a match for the three observables and for the three different isobaric chains would be highly non-trivial and would point to a common g_A^{eff} for both the single and double beta decays.
- Method MII: In the second method we relax the above-discussed idea of a common g_A^{eff} for both the single and $2\nu\beta\beta$ decays and proceed as follows: step (i): we take both g_{pp} and g_A^{eff} to be independent parameters and try to fix their values by reproducing the experimental $\log ft$ values of both the EC and β^- branches of decay. This is also quite non-trivial if it can be achieved for all the three chains of isobars. Step (ii): by using the g_{pp} value extracted in step (i) we compute the value of the theoretical $2\nu\beta\beta$ NME. Step (iii): we determine a new value of g_A^{eff} such that we can fit the experimental $2\nu\beta\beta$ half-life using the theoretical NME computed in step (ii). Now we can compare the two values of g_A^{eff}, extracted in steps (i) and (iii), to see how close they are to each other, i.e. are the g_A^{eff} values of single and $2\nu\beta\beta$ decays the same? In an ideal case the two values of g_A^{eff} would be the same and we would regain the result of the method MI above.

In summary, we want to explore by the above-discussed two methods whether simultaneous description of single-beta and $2\nu\beta\beta$ observables is at all possible or can be achieved by one single value or two different values of g_A^{eff}. It is an other matter whether the present results, obtained within the pnQRPA formalism, can be interpreted as generally valid or are just characteristic of the QRPA formalism. We make an attempt to elucidate also this point in this Letter by comparing our results with those extracted from other theory frameworks that are quite different from the pnQRPA.

2. Brief outline of the theoretical framework

Here we present briefly the formalism that we use to compute the double-beta nuclear matrix elements as well as the Gamow–Teller EC and β^- decay amplitudes and the associated $\log ft$ values.

2.1. The $2\nu\beta\beta$-decay amplitude

The $2\nu\beta\beta$-decay half-life, $t_{1/2}^{(2\nu)}$, for a transition from the initial ground state, 0_i^+, to the final ground state, 0_f^+, can be compactly written in the form

$$\left[t_{1/2}^{(2\nu)}\left(0_i^+ \to 0_f^+\right)\right]^{-1} = g_A^4 G_{2\nu} \left|M^{(2\nu)}\right|^2, \tag{2}$$

where g_A is the weak axial-vector coupling constant and $G_{2\nu}$ stands for the leptonic phase-space factor without including g_A in a way defined in [21]. The involved nuclear matrix element is written as

$$M^{(2\nu)} = \sum_{mn} \frac{M_F(1_m^+)\langle 1_m^+|1_n^+\rangle M_I(1_n^+)}{D_m}. \tag{3}$$

The amplitudes connecting the initial ground state 0_i^+ and the final ground state 0_f^+ to the intermediate 1^+ states are

$$M_I(1_n^+) = \left(1_n^+ \left\| \sum_k t_k^{\pm} \boldsymbol{\sigma}_k \right\| 0_i^+\right),$$
$$M_F(1_m^+) = \left(0_f^+ \left\| \sum_k t_k^{\pm} \boldsymbol{\sigma}_k \right\| 1_m^+\right), \tag{4}$$

respectively, where $t_k^{\pm}$ is the flavor-changing operator for the k-th nucleon in the EC or β^- direction. The quantity D_m is the energy denominator containing the average energy of the 1^+ states emerging from the two pnQRPA calculations, one for the initial nucleus and the other for the final nucleus. The denominator can thus be written as

$$D_m = \left(\frac{1}{2}\Delta + \frac{1}{2}\left[E(1_m^+) + \tilde{E}(1_m^+)\right] - M_i c^2\right)/m_e c^2, \tag{5}$$

where Δ is the nuclear mass difference of the $\beta\beta$ initial and final ground states, $\tilde{E}(1_m^+)$ is the energy of the m-th 1^+ state in a pnQRPA calculation based on the initial ground state, $E(1_m^+)$ the same for a calculation based on the final ground state and $M_i c^2$ is the mass energy of the initial nucleus. The quantity $\langle 1_m^+|1_n^+\rangle$ is the overlap between the two sets of 1^+ states [2].