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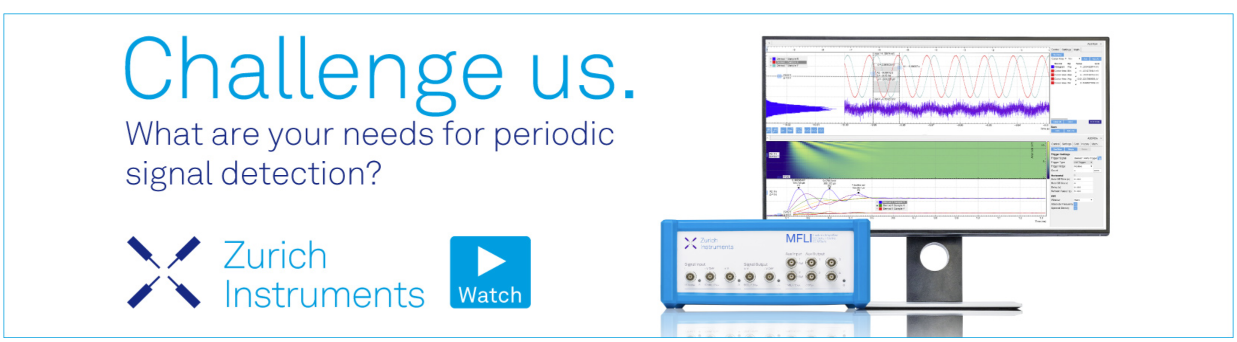

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Neutrino-nuclear responses and the effective value of weak axial coupling

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Abstract. On-going measurements of the neutrinoless $\beta\beta$ decay are accompanied by the growing interest in computing the values of the associated nuclear matrix elements. In order to extract the neutrino mass from the potentially measured $\beta\beta$ half-lives one not only needs to know the values of the nuclear matrix elements but also the effective value of the weak axial-vector coupling constant g_{A} since its value affects strongly the $\beta\beta$ half-lives. In order to gain knowledge of the possible quenching of g_{A} in finite nuclei one can study, e.g., allowed Gamow-Teller β decays. A new promising tool to study the quenching are the measurements of ordinary muon capture transitions for which the range of momentum exchange, some 100 MeV, corresponds to the one of neutrinoless $\beta\beta$ decay.

Introduction

The neutrinoless double beta ($0\nu\beta\beta$) decay of atomic nuclei can be mediated by a massive Majorana neutrino. The implications of detecting this decay are far-reaching and discussed in recent reviews [1, 2, 3]. In the case of $0\nu\beta\beta$ decay a lot of discussion is concentrated on an accurate calculation of the associated nuclear matrix elements (NMEs). However, in addition to the NMEs one needs to know the effective value of the weak axial-vector coupling g_{A} since the $\beta\beta$ half-life is quite sensitive to it [4]. The effective axial coupling relevant for $0\nu\beta\beta$ decay can be denoted as $g_{\mathrm{A},0\nu}^{\mathrm{eff}}(J^{\pi})$ since, in principle, it can depend on the multipole J^{π} of a state in the intermediate nucleus. The low momentum-exchange limit of this coupling,

$$g_{\mathrm{A},0\nu}^{\mathrm{eff}}(J^{\pi}) \xrightarrow{q\to 0} g_{\mathrm{A}}^{\mathrm{eff}}(J^{\pi}) \,, \tag{1}$$

where q denotes the exchanged momentum, can in principle be determined in single β and two-neutrino double beta ($2\nu\beta\beta$) decays [3]. In particular, the Gamow-Teller β and $2\nu\beta\beta$ decays can access the usual effective g_{A}, namely

$$g_{\mathrm{A}}^{\mathrm{eff}} \equiv g_{\mathrm{A}}^{\mathrm{eff}}(1^{+}) \,. \tag{2}$$

In addition to the β and $\beta\beta$ decays the effective value of the axial coupling plays a role in neutrino and astrophysics e.g. in the form of low-energy neutrino-nucleus scattering (solar and supernova neutrinos) and nuclear muon capture. Deviations of the effective value from the bare nucleon value $g_{\mathrm{A}} = 1.27$ can stem from shifts of decay strengths to isovector giant multipole resonances and to non-nucleonic degrees of freedom, like the Δ resonances [3]. Such effects can also be produced by nucleon currents beyond the simple impulse approximation, like the two-body meson-exchange currents [5], or deficiencies in the nuclear many-body approaches, like too restricted single-particle valence spaces, lack of important many-nucleon configurations and omission of three-nucleon forces [3, 5].

Values of $g_{\mathrm{A}}^{\mathrm{eff}}$ from Gamow-Teller β decays

The renormalization of g_{A} has long been studied for the Gamow-Teller β decays in the framework of the interacting shell model (ISM). In these calculations, reviewed in Fig 1, it appears that the value of g_{A} is quenched, and the stronger the heavier the nucleus. The renormalization of g_{A} in the ISM includes all the possible sources of deficiency listed in the introduction. In Fig. 1 the ISM results of Caurier *et al.* [6] (dark horizontal bars indicating the mass range),

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Iwata *et al.* [7] (the cross at the mass number $A = 48$), Martínez-Pinedo *et al.* [8] (M-P1996, gray hatched horizontal box), Kumar *et al.* [9] (the two black horizontal boxes), Horoi *et al.* [10] (horizontal dashed line) and Siiskonen *et al.* [11] (crosses inside circles) are contrasted against those obtained using the proton-neutron quasiparticle random-phase approximation (pnQRPA) in the works [12, 13, 14] (see the reviews [3, 15]). The pnQRPA results constitute the light-hatched regions in the background of the ISM results. The width of the regions reflects the rather large variation of the determined $g_{\rm A}^{\rm eff}$ for β-decay transitions in different isobaric chains (for more information see the reviews [3, 15]). As can be seen in the figure, the trends of the ISM results and the pnQRPA results are similar, which is non-trivial considering the drastic differences in their many-body philosophy.

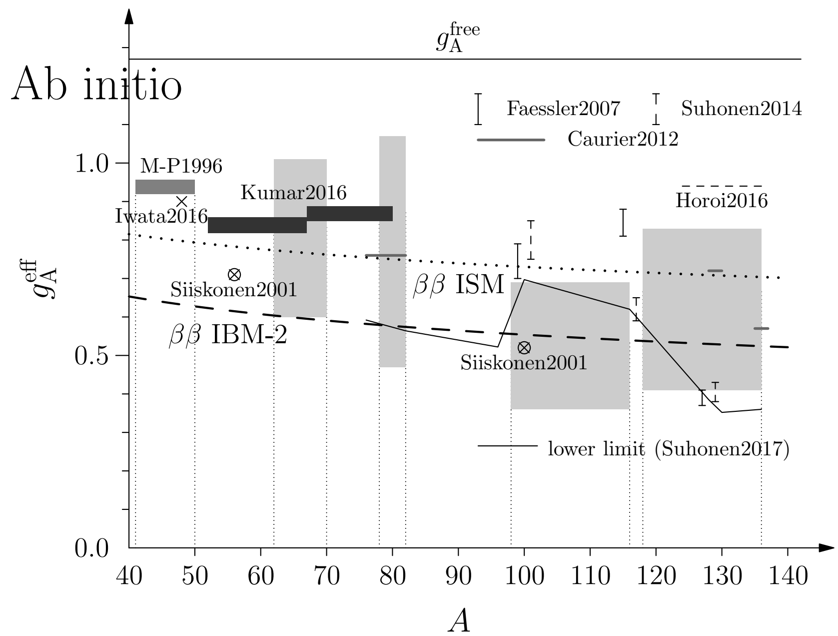

FIGURE 1. Effective values of $g_{\rm A}$ in different theoretical β and $2\nu\beta\beta$ analyses for the nuclear mass range $A = 41 - 136$. The quoted references are *Suhonen2017* [4], *Caurier2012* [6], *Faessler2007* [17], *Suhonen2014* [19] and *Horoi2016* [10]. These studies are contrasted with the ISM Gamow-Teller β-decay studies of *M-P1996* [8], *Iwata2016* [7], *Kumar2016* [9] and *Siiskonen2001* [11]. The dashed and dotted curves come from the analysis of [16]. The very recent results [5] for light nuclei in the mass range $A \leq 46$, as obtained by using ab-initio methods including the two-body meson-exchange currents, are also included in a schematic way. For more information see the body of text.

The analyses of Barea *et al.* [16] of $2\nu\beta\beta$ half-lives against results of the ISM (the dotted $\beta\beta$ ISM curve in Fig. 1) and the microscopic interacting boson model (the dashed $\beta\beta$ IBM-2 curve in Fig. 1) give a similar trend as the ISM and pnQRPA analyses. The combined β-decay and $2\nu\beta\beta$-decay analyses of Faessler *et al.* [17] (vertical solid bars) and Suhonen *et al.* [18, 19] (vertical dashed bars) for $A = 100, 116, 128$ indicate strong variation in the effective value of $g_{\rm A}$, partly consistent with the curves of Barea *et al.* [16] and the pnQRPA analyses of the Gamow-Teller β decays. In Suhonen [4] a two-stage fit of the particle-particle parameter $g_{\rm pp}$ of the pnQRPA to the data on two-neutrino $\beta\beta$ decays was performed. In this analysis it turned out that there is a minimum value of $g_{\rm A}$ for which the maximum NME can fit the $2\nu\beta\beta$-decay half-life. This lower limit of the possible $g_{\rm A}$ values is presented in Fig. 1 as a solid broken black line. It is seen that it is in line with the dashed vertical bars of $g_{\rm A}$ ranges obtained in [18, 19] and with the solid vertical bars obtained in [17].

Here it is appropriate to note that the effective value of $g_{\rm A}$ can also be enhanced, as in the case of first-forbidden $J^+ \leftrightarrow J^-$ decays. In these cases the enhancement is coming from the two-body meson-exchange currents affecting the axial-charge nuclear matrix element and there is an interference of this enhancement and the quenching related to the usual sources of quenching of $g_{\rm A}$ [15, 20, 21].

Ordinary muon capture and $0\nu\beta\beta$ decay

The ordinary muon capture (OMC) is a process where a negative muon in an atomic orbit is captured by the nucleus quite like in the ordinary electron capture of a nucleus, except the rest mass of the muon is some 200 times the rest mass of an electron. The process can formally be written as

$$\mu^- + {}^{A}_{Z}\mathrm{X}(0^+) \rightarrow \nu_\mu + {}_{Z-1}^{\;\;A}\mathrm{Y}(J^\pi)\,, \tag{3}$$

where the muon (μ^-) is captured by the 0^+ ground state of the even-even nucleus X of mass number A and atomic number Z leading to the J^π states of its odd-odd isobar Y of atomic number $Z-1$; here J is the angular momentum and π the parity of the final state. At the same time a muon neutrino ν_μ is emitted. Thanks to the involved large momentum exchange, $q \sim 50-100$ MeV/c, the OMC can lead to final nuclear states that are both highly excited and of high multipolarity J^π, quite like in the $0\nu\beta\beta$ decay where the Majorana-neutrino exchange with $q \sim 100$ MeV induces high-excitation and high-multipolarity transitions through the virtual states of the intermediate nucleus. Thus the OMC can be considered as an ideal probe of the NMEs of the $0\nu\beta\beta$ decays. This probe corresponds to the right-branch (β^+ type of transitions) virtual transitions of the $0\nu\beta\beta$ decay.

Incentives of the OMC studies are related to the $0\nu\beta\beta$ decays and the associated in-medium renormalization of the weak axial (g_A) and induced pseudoscalar (g_P) couplings [11, 22, 23, 24, 25, 26, 27, 28], and to neutrino-nucleus interactions in general, as discussed in the recent review [3]. Recently, a pioneering theoretical and experimental study of the OMC on ^{100}Mo, populating states in ^{100}Nb in a wide excitation region, up to some 50 MeV, was conducted [29]. The rate of OMC to individual final states forms a strength function quite like in the case of (n,p) charge-exchange reactions for 1^+ final states (the Gamow-Teller strength function). The OMC strength function contains giant resonances, quite like the (p,n) type of transitions contain Gamow-Teller giant resonance and isovector spin-multipole resonances [30, 31]. The work [29] uses the powerful OMC formalism of [32] and this is the first time such resonances are being studied both theoretically and experimentally, inspired by the first observation of the OMC giant resonance in ^{100}Nb at around 12 MeV [33].

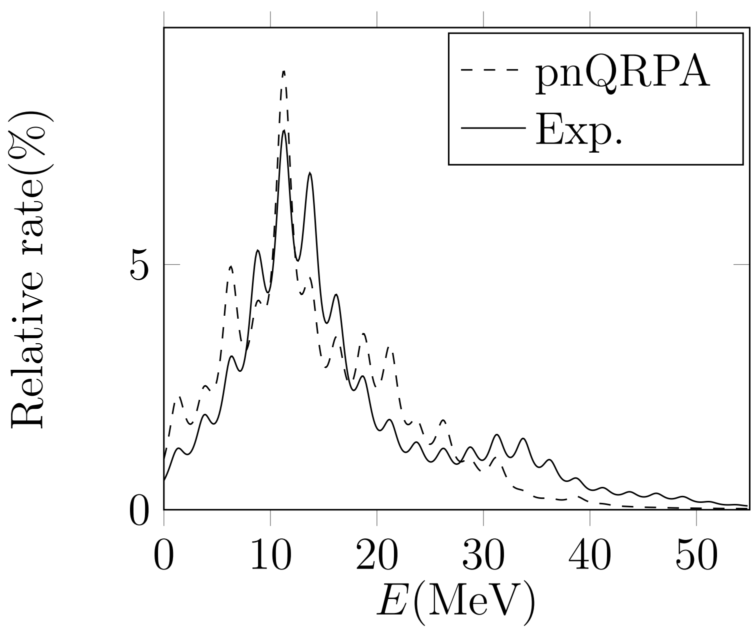

FIGURE 2. Comparison of the relative (in per cent) Lorenzian-folded muon-capture-rate distributions: theoretical capture rate to all possible final states (dashed line) is compared with the experimental strength distribution (solid line). The theoretical rate was computed with axial-coupling value $g_\mathrm{A}(0) = 0.8$ and pseudoscalar-coupling value $g_\mathrm{P}(0) = 7.0$.

Comparison of the computed and measured OMC strength functions in ^{100}Nb is presented in Fig. 2. We notice that the overall features both relative-rate distributions are similar: there is a strong peak at around 10 – 12.5 MeV and tails on both sides.

Eventual extension of the experiments and calculations to other nuclei, involved in $0\nu\beta\beta$ decays, helps theories better evaluate the β^+ NMEs associated with the $0\nu\beta\beta$ decays and the NMEs related to astro-(anti)neutrino interactions. In addition, the effective values of the axial-vector coupling $g_{\rm A}$ and induced pseudoscalar coupling $g_{\rm P}$ play essential roles both in $0\nu\beta\beta$ decays and OMC [3, 15].

Summary and conclusions

The quenching of the weak axial-vector coupling, $g_{\rm A}$, is an important issue considering its impact on the detectability of the neutrinoless double beta decay. The quenching of $g_{\rm A}$ has been observed, e.g., in allowed Gamow-Teller decays. The origins of the quenching seem to be both the nuclear-medium effects and deficiencies in the nuclear many-body approaches, but a clean separation of these two aspects is formidably difficult. Only the recent ab-initio calculations for light nuclei are able to disentangle these two sources of quenching.

Different ways to access the quenching have been proposed, one promising one being the ordinary muon capture which operates in a momentum-exchange range appropriate for extracting information on the neutrinoless double beta decays. Measurements of muon-capture rates for double-beta systems of nuclei can shed light on the nuclear matrix elements and weak couplings involved in the neutrinoless double beta decay.

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