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Viewpoint on β spectral shapes and nuclear muon capture

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Summary. — Experimental and theoretical studies of neutrinoless double beta ($0\nu\beta\beta$) decay are in the forefront of current particle and nuclear physics. Once found, $0\nu\beta\beta$ will have profound implications for the beyond-the-standard-model (BSM) physics. A crucial part of this mission is a reliable computation of the associated nuclear matrix elements (NMEs). In addition, there is an urgent need to access the effective value of the weak axial-vector coupling g_A due to its strong effect on the sensitivity estimates of the $0\nu\beta\beta$ experiments. The quenching of g_A has thus far been studied mostly through allowed Gamow-Teller β decays, but interesting new methods in the studies of β-electron spectra of forbidden non-unique β decays offer a fruitful new way of probing values of g_A. Both theoretical and experimental activity on this subject now expands rapidly and may lead to breakthroughs in future. However, all these studies probe the value of g_A at low momentum exchanges, whereas for high momentum exchanges, in the range of 100 MeV/c, relevant for $0\nu\beta\beta$ decay, a new probe, the ordinary muon capture (OMC), can be engaged. New muon-producing facilities are in operation and presently an increasing number of measurements of the OMC properties is being carried out. This holds promise for an expansion of future studies of $0\nu\beta\beta$ decays from this complementary point of view.

1. – Introduction

The implications of detection of the neutrinoless double beta ($0\nu\beta\beta$) decay are fundamental as discussed from a broad perspective in the recent reviews [1-4]. The major running and future experiments of $0\nu\beta\beta$ decay probe the $\beta^-\beta^-$ side of double beta decays, with a number of different mechanisms which can interfere [1, 5]. Lots of effort has recently been invested in calculation of the nuclear matrix elements (NMEs) related to the $0\nu\beta\beta$ decay, in particular the Majorana-mass mode [4].

Beside the NMEs, an additional uncertainty is related to the effective value of the weak axial-vector coupling g_A, the $0\nu\beta\beta$ half-life being proportional to the inverse $4th$ power of g_A [6-8]. The effective value of the axial coupling, $g^\mathrm{eff}_{\mathrm{A},0\nu}(J^\pi)$, depends on the momentum exchange q (around 100 MeV/c for $0\nu\beta\beta$ decay) and may also depend on the multipole J^π of a state in the intermediate nucleus of the decay. The low-momentum-exchange value of g_A has been studied in several works via allowed Gamow-Teller β decays, first- and higher-forbidden unique and non-unique β decays, and two-neutrino $\beta\beta$ decays, see the reviews [2, 7, 8].

In addition to β and $\beta\beta$ decays the effective value of the axial coupling plays a role in neutrino-nucleus interactions in general, *e.g.*, in the scattering of astrophysical and accelerator neutrinos off nuclei and in the ordinary muon capture (OMC) [2]. Deviations from the free-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 [2], from two-body meson-exchange currents [9], and/or deficiencies in the nuclear many-body approaches [2, 9].

In recent years, there is a booming interest in studies of β electrons (electrons emitted in β^- decays) and their energy distributions, the so-called β-electron spectra. Experimental and theoretical information on these spectra is crucial for, *e.g.*, resolving the anomalies related to the antineutrino flux from nuclear reactors and for accessing common backgrounds in the rare-events experiments themselves. Also, pinning down the effective values of weak couplings is a considerable incentive for the present and future β shapes measuring experiments [2].

The β spectral shapes help in pinning down the effective value of g_A at low momentum exchanges. For high momentum exchanges, in the range of 100 MeV/c, relevant for $0\nu\beta\beta$ decay, a new probe, the ordinary muon capture (OMC), was proposed by Kortelainen *et al.* in the seminal works [10-12]. The OMC can probe both the wave functions of the intermediate nucleus of $0\nu\beta\beta$ decay [11, 12] and the values of weak axial couplings, see [13-16]. A review about the OMC can be found in [17].

2. – Present status

2˙1. *β spectral shapes.* – Nuclear β decays vary in complexity: from allowed to highly forbidden ones [18, 19]. Of special interest for the rare-events experiments are the forbidden non-unique β decays for which the β spectral shapes can be strongly nuclear-structure dependent through several nuclear matrix elements (NME) whose values are determined by the wave functions of the initial and final states of a β-decay transition. (β decay of a nucleus is comprised of one or more β-decay transitions).

In addition to the many NME, the (partial) half-life of a forbidden non-unique β transition depends on the values of the weak vector and axial-vector couplings, g_V and g_A [19]. The value of g_A is usually quenched relative to its bare nucleon value $g_\mathrm{A} = 1.27$ [2, 7, 8]. This can have drastic effects on the sensitivity estimates of rare-events experiments trying to detect the neutrinoless double beta ($0\nu\beta\beta$) decay [1,4,6], of crucial importance in the search for the BSM physics. Only in rare cases there is an enhancement of g_A present [20].

In [21, 22] a new method called spectrum-shape method (SSM) was introduced. Use of SSM requires a β-electron spectrum with a notable g_A dependence in its shape. Information on the effective value of g_A can be gained through comparison of computed template β spectra, for different g_A values, with the measured one. Such SSM analyses of β-spectral shapes of individual β^- transitions have been done recently for the fourth-forbidden non-unique β decays of ^{113}Cd and ^{115}In in [23-25]. The calculations were done using the microscopic quasiparticle-phonon model (MQPM), the nuclear shell model (NSM) and the microscopic interacting boson-fermion model (IBFM-2). An enhanced version of SSM (enhanced SSM) was introduced in [26, 27] and the spectral moments method (SMM) in [28]. Measurements of these β spectra are being extended also to other potentially sensitive candidates, like in the case of the ACCESS Collaboration [29].

Summed β-spectral shapes are involved in the total β spectra of nuclei relevant for the reactor antineutrino flux, like ^{92}Rb [30], and as backgrounds in rare-events experiments, stemming, *e.g.*, from radon radioactive chains, as discussed in [31]. Measurement techniques of these total spectra have recently advanced through the TAGS (total absorption gamma-ray spectroscopy) method [32-34] and its refinements [35].

2˙2. *Nuclear muon capture.* – Recently, a pioneering theoretical [36] and experimental [37] study of an OMC giant resonance at around 12 MeV of excitation in ^{100}Nb was performed, and an almost perfect correspondence between the experimental and computed OMC strength function was recorded. The correspondence of the OMC and $0\nu\beta\beta$ observables was studied lately in Jokiniemi *et al.* [38-40]. In these works both the OMC strength functions and captures to individual final states were addressed by using large no-core single-particle valence spaces and realistic effective two-body nucleon-nucleon interactions within the pnQRPA. Other recent calculations include [41, 42].

Data on the OMC on ^{76}Se was recently released in [43]. The data included capture rates to individual states below some 1 MeV of excitation in ^{76}As. The corresponding theoretical evaluation of these capture rates was performed in [39] and good correpondence with data was achieved. A very recent study of the OMC on ^{136}Ba was done in [44] in the attempt to shed light on the $0\nu\beta\beta$ decay of ^{136}Xe. Both NSM and pnQRPA calculations were performed. In this work the meson-exchange two-body currents (2BC) were added to the traditionally used one-body currents (1BC), as it was introduced in [45] for the first time within an OMC framework.

Recent measurements of the OMC have been launched in Japan [46] and PSI, Villigen, Switzerland [47].

3. – Challenges for the future

Challenges for the future include at least the following.

3˙1. *β spectral shapes.* – Measurements of the electron spectral shapes of single β transitions are expanding along with new measurement tehniques, see, *e.g.*, [29]. The challenges here concentrate on finding new g_A-sensitive candidates for measurements by using Hamiltonians of different nuclear models, *e.g.* the NSM, MQPM, IBFM-2, and the pnQRPA (proton-neutron quasiparticle random-phase approximation [18]). The multiple-commutator model (MCM), a higher QRPA scheme [48], would contribute to calculations of excited-state β transitions in the future.

Regarding the summed β electron spectra, the experiments are on the way to solve the reactor antineutrino flux anomaly, but, instead, the "bump" anomaly still remains unresolved [49-51]. On the theory side it is a formidable task to extend the total β-spectral calculations to other medium-heavy fission fragments, beyond ^{92}Rb [30], although new theoretical methods pave the way to a more reliable account of the TAGS-measured branching ratios [31].

3˙2. *Ordinary muon capture.* – For the OMC the challenges pertain to experiments and their analyses. The many neutron emissions and gamma-decay cascades after the OMC necessitate new openings also in the nuclear spectroscopy in the form of spin-parity and gamma-decay measurements of nuclear levels in the OMC daughter nuclei [43]. This makes comparison with the calculated OMC rates a challenge.

4. – Long-term perspective

Here few notes on the long-term perspective of the studies of the β spectral shapes and the OMC are laid out.

4˙1. *β spectral shapes.* – In the future more and more of the spectral shapes of individual β transitions will be measured and more g_A-sensitive candidates for measurements will be found theoretically. These methods will reach also the realm of *ab initio* calculations [52] which can be extended to heavier and heavier nuclei, in particular the open-shell ones, relevant for the spectral-shape measurements.

The long-term perspectives clearly point towards complete solution of the reactor-antineutrino anomaly by using TAGS and other advanced experimental methods. On the other hand, the summation method using theoretical inputs in the form of total β-spectral shapes may lead to the resolution of the spectral bump mystery. For this a coordinated effort of several theoreticalc groups and creation of a spectral-shape repository is necessary. In the end, it is expected that also the *ab initio* nuclear theory [52] will contribute to this challenging but rewarding mission.

4˙2. *Ordinary muon capture.* – The *ab initio* calculations of the OMC on light nuclei [45] will be extended to heavier and heavier nuclei, including open-shell cases, as well. Comparison of the results of these calculations with those of the traditional approaches (NSM, pnQRPA and potentially the microscopic interacting boson-fermion-fermion model, IBFFM-2 [53]) will be interesting, in particular in the cases where experimental data is lacking. It is probable that the OMC experiments will solve their analyses problems together with nuclear spectroscopists. Hence, the prospects of the OMC as a complemetary test of double beta decays will be bright.

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