Fundamental Physics with Electroweak Probes of Nuclei

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Abstract. The past decade has witnessed tremendous progress in the theoretical and computational tools that produce our understanding of nuclei. A number of microscopic calculations of nuclear electroweak structure and reactions have successfully explained the available experimental data, yielding a complex picture of the way nuclei interact with electroweak probes. This achievement is of great interest from the pure nuclear-physics point of view. But it is of much broader interest too, because the level of accuracy and confidence reached by these calculations opens up the concrete possibility of using nuclei to address open questions in other sub-fields of physics, such as, understanding the fundamental properties of neutrinos, or the particle nature of dark matter.

In this talk, I will review recent progress in microscopic calculations of electroweak properties of light nuclei, including electromagnetic moments, form factors and transitions in between low-lying nuclear states along with preliminary studies for single- and double-beta decay rates. I will illustrate the key dynamical features required to explain the available experimental data, and, if time permits, present a novel framework to calculate neutrino-nucleus cross sections for A > 12 nuclei.

The nuclear ab initio approach aims at describing the widest range of nuclear phenomena through interactions occurring between nucleons inside the nucleus. In this microscopic picture, nucleons interact with each other via two- and three-body interactions, and with external electroweak probes via couplings to individual nucleons and to nucleon-pairs (a contribution described by two-nucleon currents). Albeit limited to light nuclei (A ≤ 12), Quantum Monte Carlo calculations based on the AV18 [1] two-body and IL7 [2] three-body interactions successfully explain available experimental data in a broad energy range, from the keV regime relevant to astrophysics studies to the GeV regime where short-range correlations become predominant [3, 4, 5]. These studies yield a rather complex picture of the nucleus with many-body correlations in both the nuclear wave functions and electroweak currents playing an important role in reaching agreement with the data. For example, corrections from two-body electromagnetic currents are as large as 40% in the calculated magnetic moment of $^{9}$C [6], while electron scattering experiments have demonstrated the requirement of two-body currents in quasi-elastic scattering from nuclei, where they enhance the transverse response by up to $\sim$ 40% [4, 5].

The success of the microscopic picture in explaining the data both qualitatively and quantitatively is an important achievement from the nuclear physics point of view. But it is of much broader interest too, because the level of accuracy and confidence reached by these
Quantum Monte Carlo calculations opens up the concrete possibility of using nuclei to address prominent and pressing open questions in nuclear physics and their connection to fundamental physics quests.

Recently, we addressed the “$g_A$ problem”, that is the systematic overprediction ($\sim 20\%$ in $A \leq 18$ nuclei) of Gamow-Teller matrix elements in simplified nuclear calculations [7, 8]. The overprediction of the calculated matrix elements is possibly attributable to the fact that for larger nuclear systems, in order for the calculations to be computationally feasible, one has to approximate the \textit{ab initio} framework, by, \textit{e.g.}, leaving out correlations and/or truncate the model space. Another approximation that can contribute to the manifestation of the “$g_A$ problem” is in the adopted model for the nuclear axial current, which typically neglects many-body terms. In order resolve this long-standing problem, we performed numerically exact Quantum Monte Carlo calculations of Gamow-Teller matrix elements in $A = 6$–$10$ nuclei [9], accounting systematically for many-body effects in nuclear interactions and coupling to the axial one-, two- and three-body currents derived in chiral effective field theory [10, 11].

![Figure 1. (Color online) Ratios of GFMC to experimental values of the Gamow-Teller reduced matrix elements in the $^3$H, $^6$He, $^7$Be, and $^{10}$C weak transitions. Theory predictions (from Ref. [9]) correspond to the $\chi$EFT axial current in LO (blue circles) and up to N4LO (magenta stars). Green squares indicate 'unquenched' shell model calculations from Ref. [7] based on the LO axial current.](image)

Our results are summarized in Fig. 1, where we show Green’s Function Monte Carlo (GFMC) [3] calculations of the Gamow-Teller reduced matrix elements normalized to the corresponding experimental values in $^3$H, $^6$He, $^7$Be, and $^{10}$C weak transitions. The effect of many-body components in the axial current can be appreciated by comparing blue dots, based on the one-body axial current, with the magenta stars which include in addition to the one-body also two- and three-body terms in the axial current [10]. We find that the effect of many-body currents is negligible, in fact they increase by only $\sim 2$–$3\%$ the one-body Gamow-Teller contributions. On the other hand, correlations in the wave functions significantly reduce the matrix elements, a fact that can be appreciated by comparing the GFMC (blue circles in Fig. 1) and the shell model calculations (green squares in the same figure) from Ref. [7], both based
Figure 2. The left (right) panel shows the light Majorana neutrino exchange mechanism (GT-AA) distribution in $r$-space ($q$-space) for the $^{10}\text{He} \rightarrow ^{10}\text{Be}$ transition, with and without “one-pion-exchange-like” correlations in the nuclear wave functions. See text and Ref. [14] for explanation.

on the one-body axial current. The reduced matrix elements in the shell model calculations are enhanced by $\sim 8\%$ ($\sim 17\%$) in $A = 6–7$ ($A = 10$) transitions with respect to the experimental data, while inclusion of correlations in the nuclear wave functions leads to an agreement with the data that is excellent in $A = 6–7$ transitions and at the 10% level in the $^{10}\text{C}$ weak transition. The discrepancy in this last case may be attributable to deficiencies in the AV18+IL7 wave functions of $A = 10$ nuclei. In fact, GFMC calculations based on the Norfolk two- and three-nucleon chiral potentials [12, 13] and the one-body axial current, bring the $^{10}\text{C}$ prediction only $\sim 4\%$ above the experimental datum. These findings suggest that the longstanding “$g_A$-problem” may be resolved primarily by correlation effects.

While the “$g_A$-problem” in single-beta decays, limited to the transitions we have studied, seems to be largely attributable to missing correlations in the nuclear wave functions, little it is know about how it propagates at moderate values of momentum transfer. This lack of knowledge impacts ongoing world-wide experimental enterprises aimed at potentially observe neutrinoless double beta decay, a process in which two neutrons decay into two protons with the emission of two electrons but no neutrinos, thus violating the lepton number conservation by two units. The average momentum transfer in these transitions is of the order of 100 MeV [8], a scale that is set by the average distance between the two decaying neutrons. Observation of this decay would be a clear signature of physics beyond the standard model and it will have tremendous consequences on our understanding of the Majorana nature of the neutrino and the neutrino mass hierarchy, and potentially the observed matter-antimatter asymmetry in the universe. The interpretation of either a positive or null experimental result heavily relies on accurate evaluations of nuclear matrix elements. The latter are at present characterized by large theoretical uncertainties [8], primarily attributable to the fact that for nuclei relevant to experimental purposes ($A \geq 48$), one has to approximate the ab initio framework by leaving out some correlations.

In order to address how the “$g_A$-problem” propagates at moderate values of momentum transfer, we recently performed Quantum Monte Carlo calculations of neutrinoless double beta decay matrix elements in $A = 6–12$ nuclei [14]. In particular, we have studied the effect of artificially turning off correlations in the nuclear wave functions, finding a $\sim 10\%$ increase in
the calculated nuclear matrix elements for the light Majorana neutrino exchange mechanism. This corresponds to having to “quench” $g_A$ by $\sim 0.95$ to accommodate for correlation effects. On the other hand, we saw that in single-beta decay, a zero momentum transfer observable, the required “quenching” of $g_A$ in say, the $^{10}$C weak transition evaluated in the shell model, is $\sim 0.83$ as one can read off Fig. 1 but comparing the $A=10$ green square with the experimental datum (black diamond). These findings may indicate that the $g_A$ “quenching” required in calculations based on more approximated nuclear models (for $A > 12$ nuclei) is larger in single beta decay than in neutrinoless double beta decays. In Fig. 2 we show the effect of artificially turning off correlations in the nuclear wave functions when calculating the neutrinoless double beta decay matrix elements induced by the light Majorana neutrino exchange potential. In particular, in Fig. 2 the blue triangles (solid line) in the left (right) panel represent the $r$-space ($q$-space) transition distribution obtained by turning off the correlations to be compared with the red dots (solid line) obtained with the correlated wave function. The associated matrix element, obtained by integrating the distribution in $dr$ where $r$ is the inter-particle distance, undergoes a 10% increase when correlations are turned off.

We emphasize that the nuclear systems we studied in Ref. [14] are not relevant from the experimental point of view, nevertheless they are interesting and provide us with an extremely useful set of test cases to benchmark theoretical nuclear models and/or computational methods. We studied the matrix elements of light Majorana neutrino exchange potentials [16, 15] (denoted by $\nu$ in Fig. 3) as well as short-distance sources (denoted by $\pi \pi$ and $\pi N$ in Fig. 3) of lepton number violation encoded in dimension-seven and -nine operators (see Ref. [17] and references therein). These generically lead to Gamow-Teller and Fermi spin-isospin structures, in Fig. 3 denoted with GT and F, respectively. In the left and right panels of Fig. 3 we show the $q$-space transition distributions of the $^{10}$He$\rightarrow^{10}$Be and $^{12}$Be$\rightarrow^{12}$C decays, respectively. The different height of the peaks is due to the different spatial overlaps between an initial diffuse neutron distribution and a final compact proton distribution in the case of the $A=10$ transition, and between two compact initial neutron and final proton distributions in the $A=12$ transition [14].
These findings may have implications in our understanding of the dynamics entering the
neutrinoless double beta decay matrix elements in nuclei of experimental interest.

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