Neutrino-nucleus reactions in the energy range 1-100 MeV

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We review some salient aspects of calculations of the neutrino-nucleus reaction cross sections in the low energy range (1-100 MeV).

1. Introduction

Neutrino-nucleus reactions in the low-energy region are important for multiple reasons (see \textit{e.g.}, [1,2]). First, neutrino-nucleus reactions play important roles in many astrophysical processes including stellar nucleosynthesis. Second, the observation of neutrinos emitted in various astrophysical processes provides valuable information in both astrophysical and particle-physics contexts, and most of terrestrial experiments to measure the astrophysical neutrinos use nuclear targets. Third, the investigation of the neutrino properties with the use of accelerator neutrinos also very often employs nuclear targets. All these studies call for sufficiently accurate estimates of the cross sections for various neutrino-nucleus reactions. It is obviously beyond the scope of this short note to discuss all of these individual cases. We instead concentrate on several selected examples which help convey the basic features of calculations involved in low-energy neutrino-nucleus reactions. Since the description of a $\nu$-nucleus reaction becomes increasingly complicated as the target mass number $A$ gets larger, it is illuminating to first discuss the $\nu$-$d$ reactions ($A = 2$) as the theoretically most tractable case. We then proceed to give a brief discussion of the $\nu$-$^{12}$C and $\nu$-$^{16}$O reactions and finally we add a few comments on the neutrino reactions on medium-heavy and heavy nuclei. We start with the explanation of two theoretical frameworks (SNPA and EFT) that are of general relevance in describing electroweak processes in light nuclei.

2. Standard nuclear physics approach (SNPA)

In nuclear physics, the phenomenological potential picture has been highly successful. In this picture an $A$-nucleon system is described by a Hamiltonian of the form

$$ H = \sum_{i} t_i + \sum_{i \neq j} V_{ij}^{\text{phen}} + \cdots, \quad (1) $$

where $t_i$ is the kinetic energy of the $i$-th nucleon, $V_{ij}^{\text{phen}}$ is a phenomenological two-body potential between the $i$-th and $j$-th nucleons, and the dots represent potentials involving three or more nucleons (which are much less important than $V_{ij}^{\text{phen}}$). The nuclear wave function $|\Psi\rangle$ is

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obtained by solving the Shr"odinger equation
\[ H|\Psi\rangle = E|\Psi\rangle. \] (2)

Traditionally, finding useful truncation schemes for \(|\Psi\rangle\) has been an important branch of nuclear physics (the shell model, cluster model, etc.) but, thanks to the progress in numerical computation techniques [3], it is now possible to directly solve eq.(2) for light nuclei \((A \leq 11)\). The phenomenological nature of \(V_{ij}^{\text{phen}}\) is reflected in the fact that its short-distance behavior is model-dependent. (The large-distance behavior of \(V_{ij}^{\text{phen}}\) is controlled by the requirement that \(V_{ij}\) should approach the Yukawa potential.) One therefore assumes a certain functional form for \(V_{ij}^{\text{phen}}\) and adjust the parameters appearing therein so that the solutions of eq.(2) for the \(A=2\) case reproduce the two-nucleon observables. There are by now a number of so-called modern high-precision phenomenological N-N potential that can reproduce all the existing two-nucleon data with normalized \(\chi^2\) values close to 1 [4]. To describe nuclear responses to external electroweak probes, we use transition operators that consist of the dominant one-body terms (or the impulse approximation (IA) terms) and exchange-current (EXC) terms, which represent the contributions of nuclear responses involving two or more nucleons. These transition operators are derived in such a manner that they are consistent with the nuclear Hamiltonian in eq.(1) and satisfy the low-energy theorems and current algebra [5]. The theoretical framework summarized here is a cornerstone of contemporary nuclear physics (for a review, see e.g., [3]), and it is becoming common to refer to it as the standard nuclear physics approach (SNPA), the term apparently first used in [6]. SNPA has been scoring great phenomenological successes in correlating and explaining a vast variety of nuclear phenomena [3].

3. Effective field theory (EFT)

A new approach based on effective field theory (EFT) is rapidly gaining ground in nuclear physics. The basic idea is that, in describing phenomena characterized by a typical energy-momentum scale \(Q\), we need not include in our Lagrangian those degrees of freedom that pertain to energy-momentum scales much higher than \(Q\); they can be “integrated out” with only active low-energy degrees of freedom (or effective fields) retained. The effective Lagrangian, \(\mathcal{L}_{\text{eff}}\), governing low-energy dynamics turns out to be given by the sum of all possible monomials of the effective fields and their derivatives that are consistent with the symmetry requirements of the original Lagrangian. Since a term involving \(n\) derivatives scales like \((Q/\Lambda)^n\) (\(\Lambda\) is a certain cutoff scale), the terms in \(\mathcal{L}_{\text{eff}}\) can be organized into a perturbative series in which \(Q/\Lambda\) serves as an expansion parameter. The coefficients of terms in this expansion scheme are called the low-energy constants (LECs). If all the LEC’s up to a specified order \(n\) can be fixed either from theory or from fitting to the experimental values of the relevant observables, \(\mathcal{L}_{\text{eff}}\) serves as a complete (and hence model-independent) Lagrangian to the given order of expansion. These considerations, applied to hadronic systems, lead to an EFT of QCD known as chiral perturbation theory \((\chi\text{PT})\). A variant of \(\chi\text{PT}\), called heavy-baryon chiral perturbation theory \((\text{HB}\chi\text{PT})\) [7], is used for a system involving a nucleon. However, \(\text{HB}\chi\text{PT}\) cannot be applied in a straightforward manner to nuclei because the existence of very low-lying excited states in nuclei invalidates perturbative treatments. Following Weinberg [8], we avoid this difficulty as follows. We classify Feynman diagrams into two groups. Diagrams in which every intermediate state has at least one meson in flight are categorized as irreducible, and all other diagrams are called reducible. We apply the chiral counting rules only to irreducible diagrams. The contribution of all the two-body irreducible diagrams (up to a specified chiral order) is treated as an effective potential (to be denoted by \(V_{ij}^{\text{EFT}}\)) acting on nuclear wave functions. Meanwhile, the contributions of reducible diagrams can be incorporated by solving the Schrödinger equation
\[ H_{\text{EFT}}|\Psi_{\text{EFT}}\rangle = E|\Psi_{\text{EFT}}\rangle, \] (3)
where
\[ H_{\text{EFT}} = \sum_i t_i + \sum_{i<j} V_{ij}^{\text{EFT}}, \] (4)
We refer to this two-step procedure as nuclear \( \chi PT \), or, to be more specific, nuclear \( \chi PT \) in the Weinberg scheme.\(^4\) To apply nuclear \( \chi PT \) to a process that involves (an) external current(s), we derive a nuclear transition operator \( T^{\text{EFT}} \) by evaluating the complete set of all the irreducible diagrams (up to a given chiral order \( \nu \)) involving the relevant external current(s). To preserve consistency in chiral counting, the nuclear matrix element of \( T^{\text{EFT}} \) must be calculated with the use of nuclear wave functions which are governed by nuclear interactions that represent all the irreducible A-nucleon diagrams up to \( \nu \)-th order. Thus, a transition matrix in nuclear EFT is given by

\[
M^\text{EFT}_{fi} = \langle \Psi^\text{EFT}_f | T^{\text{EFT}} | \Psi^\text{EFT}_i \rangle, \tag{5}
\]

where the superscript “EFT” means that the relevant quantities are obtained according to EFT as described above. If this program is carried out exactly, it would constitute an \textit{ab initio} calculation. In actual calculations, however, it is often very useful to adopt in eq.\( (5) \) wave functions obtained from SNPA. This eclectic approach, called hybrid EFT, can be used for complex nuclei (\( A = 3, 4, \ldots \)) with essentially the same accuracy and ease as for the A=2 system [11,12].

4. \( \nu\text{-}d \) reactions

As is well known, the \( \nu\text{-}d \) reactions are of particular importance in connection with the SNO experiments [13]. On the theoretical side, because of their relative simplicity the \( \nu\text{-}d \) reactions serve as pilot cases for demonstrating the reliability of the available calculational frameworks.

Nakamura \textit{et al.} [14,15] performed detailed SNPA calculations of the cross sections for the reactions: \( \nu_x d \to e^\pm pp, \nu_x d \to \nu_x pm, \nu_x d \to e^\pm nn, \bar{\nu}_x \to \bar{\nu}_x pm \) (\( x=e, \mu \) or \( \tau \)). The strength of the exchange current (dominated by the \( \Delta \)-particle excitation diagram) was fixed by fitting the experimental value of the tritium \( \beta \)-decay rate \( \Gamma^3 \). The results of Nakamura \textit{et al.} are considered to be reliable at the 1 \% level in the solar neutrino energy range \( (E_\nu \leq 20 \text{ MeV}) \), and at the 5\% level up to the pion-production threshold energy. The basis for this statement is as follows. First, many electroweak observables in light nuclei calculated with SNPA indicate this degree of reliability of SNPA [3,16]. Second, for the solar energy region, the SNPA results are supported by EFT calculations as well. Butler, Chen and Kong [17] carried out an EFT calculation of the \( \nu\text{-}d \) cross sections, using the KSW scheme [9]. Butler \textit{et al.}'s results (after one unknown LEC is adjusted) are consistent with those of Nakamura \textit{et al.} [15]. Further support comes from Ando \textit{et al.}'s calculation [18]. As mentioned, hybrid \( \chi PT \) allows us to treat nuclei with different mass numbers on the equal footing. Park \textit{et al.} [19,20], applying hybrid \( \chi PT \) to the GT transitions in the \( A=2, 3 \) and 4 systems, noticed that only one unknown LEC (denoted by \( \hat{d}_R \)) appears, and that \( \hat{d}_R \) can be determined with good precision from \( \Gamma^3 \). Hybrid \( \chi PT \) used in this manner is called EFT* [21,22].\(^5\) Ando \textit{et al.} [18] used the same EFT* approach to carry out a parameter-free calculation of the \( \nu\text{-}d \) cross sections, and their results agree with those of Nakamura \textit{et al.} [15] within 1 \%. Thus, at least in the solar neutrino energy region, the SNPA calculation has solid support from a more fundamental approach (EFT or EFT*), and the nature of SNPA is such that its validity is expected to extend up to the pion production threshold \( (E_\nu \leq 130 \text{ MeV}) \).\(^6\)

5. \( \nu\text{-}^{12}C \) reactions and \( \nu\text{-}^{16}O \) reactions

As the mass number \( A \) of the nuclear target gets larger, it becomes difficult to carry out full SNPA calculations of \( \nu\text{-}A \) reactions, which forces us to introduce certain approximate treatments of the nuclear wave functions. To illustrate issues involved in these approximations, we discuss here the \( \nu\text{-}^{12}C \) reactions \( \nu\text{-}^{16}O \) reactions. It is to be noted that \( ^{12}C \) is an ingredient of liquid scintillators and \( ^{16}O \) is the basic component of water

\(^5\)It is also called “more effective” effective field theory (MEEFT) [12].

\(^6\)The tabulation of the total and differential cross sections for the \( \nu\text{-}d \) reactions calculated by Nakamura \textit{et al.} [14,15] is available at:

\(<\text{http://boson.physics.sc.edu/~gudkov/NU-D-NSGK}>\),

and \(<\text{http://www-nuceth.phys.sci.osaka-u.ac.jp/top}>\).

\(^4\)For an alternative form of nuclear EFT based the KSW scheme [9], see, \textit{e.g.}, Ref. [10].
Čerenkov counters.

The best studied method for truncating nuclear wave functions is the shell model, in which we introduce an average single-particle potential \( V_{\text{ave}} \) to generate single-particle orbitals from which A-body wave functions are formed. If we use as \( V_{\text{ave}} \) the harmonic oscillator (HO) potential (known to be a good approximation for describing bound states in light nuclei), the degree of truncation of nuclear wave functions can be specified by stating how many excited HO configurations \((nh\omega)\) are included in the calculation. In the use of a truncated model space, the nucleon-nucleon interactions as well as transition operators for various nuclear observables get renormalized into effective operators, which may be schematically denoted by \( V_{NN}^{\text{eff}} \) and \( T_{\text{eff}} \), respectively. (This is similar to what happens with the introduction of an EFT.) There exist two ways to get information on \( V_{NN}^{\text{eff}} \) and \( T_{\text{eff}} \). In one method they are derived from the “bare” forms (pertaining to untruncated cases) by incorporating the contributions of virtual states which lie outside the chosen model space [23]. In the second method, we simply list all formally allowed terms for \( V_{NN}^{\text{eff}} \) or \( T_{\text{eff}} \) and determine their prefactors by fitting to the available experimental data. Insofar as the number of parameters to be fixed is sufficiently smaller than the number of data points, this effective operator method (EEOM) has predictive power [24–26].

For closed-shell light nuclei such as \(^{16}\text{O}\), one can handle a relatively large model space; for instance, a shell-model calculation including up to \( 4\hbar\omega \) configurations was reported [27]. For nuclei away from shell closures the situation is less favorable, and one is forced to use certain approximations instead of full shell-model diagonalization. \(^{12}\text{C}\) belongs to this category, and the random phase approximation (RPA) is commonly used for this case [28]. (See however a recent no-core shell model calculation for the \( A=12 \) system by Hayes et al. [29].)

In assessing the reliability of using the shell model and its approximations in calculating \( \nu\)-nucleus reactions, we need to pay attention to an apparent anomaly known for the inclusive reaction \(^{12}\text{C}(\nu_\mu, \mu)^{12}\text{N}^*\) [30]. According to an LSND experiment [30], for \( 123.7 \text{ MeV}<E_\nu<280 \text{ MeV} \), the measured flux-averaged inclusive cross section was more than a factor of 2 lower than that predicted by the Fermi-gas model [31] and by an RPA calculation [35]. Although the incident neutrino energies in this experiment lie above the energy region mentioned in the title of this talk, the range of nuclear excitations involved in this experiment are relevant to lower-energy \((E_\nu<100 \text{ MeV})\) neutrino reactions as well. It therefore concerns us whether there is really an anomaly in the \(^{12}\text{C}(\nu_\mu, \mu)^{12}\text{N}^*\) reaction. When the final report on the LSND experiment appeared [36], the measured flux-averaged cross section was still significantly lower than the existing theoretical predictions of the time. Most recently, however, there has been much progress on the theoretical side. Within RPA, Krmpotić et al. [37] report that the implementation of particle-number conservation in quasi-particle RPA brings the theoretical prediction into agreement with experiment. Meanwhile, Oset and his collaborators have developed a formalism which incorporates long-range nuclear correlations via RPA, and which in addition accounts for final-state interactions and the Coulomb corrections. Their very recent work [34] reports that there is no anomaly in the \(^{12}\text{C}(\nu_\mu, \mu)^{12}\text{N}^*\) reaction. Furthermore, in a no-core shell model calculation [29], Hayes et al. point out that the inclusion of a realistic three-body interaction can remove the discrepancy between theory and experiment. All these developments indicate that the long-standing “anomaly” is finally gone and that there is no basic problem with the currently available nuclear physics approaches.

Haxton [38] was the first to point out the importance of the \( \nu-^{16}\text{O} \) reaction in water Čerenkov counters, and he calculated the relevant cross section, using \( 2\hbar\omega \) shell-model wave functions and the transition operators whose strength are renormalized according to EEOM. Here, the inclusive nature of the reaction under consideration is

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\(^7\)A recent study [32] has questioned the quantitative reliability of the Fermi-gas even in the quasi-elastic scattering regime. See also [33,34].
taken into account by summing all energetically allowed final bound states of the A=16 nuclear system. Interestingly, Kuramoto et al.’s calculation [39] based on the relativistic Fermi gas model (RFGM) [40] indicates that the RFGM cross sections and Haxton’s results can be smoothly extrapolated into each other at around \( E_\nu = 60 \) MeV; see also Bugaev et al. [41]. The most recent examples of a calculation for the \( \nu^{16}\text{O} \) reaction can be found in [42,34].

6. Neutrino reactions on medium-heavy and heavy nuclei

The study of low-energy neutrino reactions on medium-heavy and heavy nuclei is of great current importance in various contexts. For one thing, some nuclei of this category are either used or planned to be used in solar neutrino experiments with various specific features. Furthermore, many reactions of this type play important roles in supernova explosions and neutrino nucleosynthesis, see e.g. [43]. It is to be noted that, depending on the condition of a core that occurs in stellar collapse, the average electron-neutrino energy can range typically from 10 to 50 MeV, and that cross sections for \( \nu_e \) capture on iron-group nuclei through \( A=100 \) are needed to accurately simulate core depleptonization and to accurately determine the post-bounce initial condition [43].

Providing sufficiently accurate estimates of the cross sections for all the relevant neutrino-nucleus reactions is one of the imminent challenges facing nuclear physics. To push ultra-large scale shell-model calculations (or, if possible, even SNPA calculations) for higher and higher mass numbers is an important direction of theoretical efforts. However there will be quite sometime before these frontal attacks can cover all the relevant nuclides. The best strategy one could take at present is to use a model (such as RPA or EEOM) that can cover a wide range of nuclides and to improve or gauge its reliability with the help of experimental data. For instance, Langanke et al. [44] considered the possibility of utilizing EEOM and high-resolution electron scattering experiments to calibrate neutrino-nucleus cross sections relevant to supernova neutrinos. It is also noteworthy that there exists an experimental project [45] which, taking advantage of ultra-high-intensity neutrino beams that will become available at the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory, aims at measuring the cross sections of several neutrino-nucleus reactions with hitherto unachievable precision. These experiments are expected to shed much light on the reliability and the predictive power of nuclear models to be used for studying supernova explosion and nucleosynthesis.

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