FACETS OF NEUTRINO–NUCLEUS INTERACTIONS*

A.B. Balantekin

University of Wisconsin, Department of Physics, Madison, Wisconsin 53706, USA

Different approaches to the calculation of neutrino–nucleus cross sections are summarized. Potential impact of improving the nuclear physics input into neutrino interactions and cross-section calculations on uncovering new physics is discussed using the example of reactor anomaly. Importance of a thorough understanding of neutrino interactions in astrophysics and cosmology is highlighted.

1. Introduction

Neutrino physics is closely connected to nuclear physics, a connection which goes beyond the evident connection between neutrino detection and the nuclear structure of the target isotopes. For example, in a core-collapse supernova, understanding neutrino cooling of the newly formed proto-neutron star benefits from knowledge of the nuclear equation of state. In such environments or in merging of two neutron stars, neutrinos determine the neutron-to-proton ratio, the parameter controlling yields of nucleosynthesis. An old problem in nuclear physics is to accurately calculate neutrino–nucleus cross-sections and beta-decay rates. A firm knowledge of the nuclear matrix elements for the neutrinoless double beta decay is crucial to assess the experimental outlook for observing possible violation of lepton number, a fundamental symmetry of the Universe. For many aspects of supernova physics, we need to know what happens when a 10 to 40 MeV neutrino hits a nucleus. Longstanding questions include distribution of the Gamow–Teller and tensor strengths as well as the value of the effective axial-vector strength factor, g_A. As the incoming neutrino energy increases, the contribution of hard to calculate expectation values increase, including first- and even second-forbidden transitions. Forbidden transitions may be the key to understand decays of isotopes in the nuclear fuel of power reactors and the resulting reactor neutrino spectra.

---

* Presented at the XXXV Mazurian Lakes Conference on Physics, Piaski, Poland, September 3–9, 2017.

Several recent experiments emphasize the need for better nuclear data in connection with fundamental science, either exploring new physics beyond the Standard Model or exploring astrophysical phenomena. For example, short-baseline reactor neutrino experiments successfully measured the neutrino parameters they set out to measure, but they also identified an excess of reactor antineutrinos with energies around 5 MeV as well as a reduction from the predicted value of the flux [1–4]. This result raises some very interesting nuclear physics questions regarding neutrino interactions, some of which we discuss below.

A key development during the last few decades has been the appreciation of the close relationship between neutrinos and nucleosynthesis as physicists and astronomers ascertained the fact that neutrino properties figure prominently in many astrophysical environments. Consequently, all the properties of neutrinos could significantly impact description of astrophysical environments. Understanding where and how various nuclei are synthesized during the evolution of the Universe is one of the key questions of modern science. Element synthesis is thought to be a multi-site and multi-epoch process. Tackling the question of the origin of elements requires a multitude of tools: High-quality observations of stellar spectra, laboratory atomic physics data, modeling stellar photospheres as well as theoretical and experimental investigations of the relevant nuclear processes. Typically, copious amounts of neutrinos are present in most nucleosynthesis sites. This feature makes neutrino physics and neutrino–nucleus interactions salient components of many nucleosynthesis scenarios. The interaction of the neutrinos with ordinary matter is rather feeble except when the density is very large. Consequently, neutrinos can easily transfer a significant amount of energy and entropy over astronomical distances. (For example, almost the entire gravitational binding energy of a pre-supernova star is released as neutrinos.) Clearly, such energy transfers could be very important in astrophysics and cosmology, making a thorough understanding of neutrino interactions crucial to explore many such phenomena.

Status and challenges of neutrino–nucleus scattering for a wide range of energies was recently summarized in Ref. [5]. In this proceedings contribution, the discussion is limited to a few examples of interactions of neutrinos with very low energies (up to few tens of MeV) and nuclei.

2. Some cross-section calculations

In this section, calculations of three different neutrino–nucleus cross sections, chosen to illustrate three different techniques utilized to calculate such cross sections, are briefly discussed.

Determining the interaction between two nucleons is a long-standing problem. During the last decade, both the nuclear structure physics and nuclear reactions communities increasingly made use of the effective field theory approach. With the advent of the effective field theory methods, there had been a renewed interest in deriving the nucleon–nucleon interaction from the fundamental theory. In effective field theories describing low-energy physics, one integrates over the degrees of freedom associated with physics coming into play at higher energies. However, one has to introduce counter terms to cancel divergences which may arise at higher orders. At energies below the pion threshold, nucleon–nucleon interaction is particularly simple: $^3S_1 \to ^3S_0$ transition dominates and one has to introduce a single counter term, dubbed L_{1A}, characterizing the unknown isovector axial two-body current. The cross sections for the reactions

$$\nu_e + d \to p + p + e^-$$

and

$$\overline{\nu}_e + d \to n + n + e^+$$

can then be calculated in a pionless effective field theory as a function of this unknown term [6, 7]. The resulting cross sections can be written as

$$\sigma(E_\nu) = \sigma_0(E_\nu) + L_{1A}\,\sigma_1(E_\nu)\,,$$

where the terms $\sigma_0(E_\nu)$ and $\sigma_1(E_\nu)$ can be easily evaluated. The value of L_{1A} can be estimated either from reactor anti-neutrino deuteron breakup reactions [8] or from solar neutrino experiments [9–11]. From these considerations, one obtains a value of $L_{1A} \sim 4$ fm^3. Very recently, this parameter was calculated using lattice QCD at a renormalization scale set by the physical pion mass to be $L_{1A} = 3.9(0.1)(1.0)(0.3)(0.9)$ fm^3 [12]. Hence, we have an accurate description of weak breakup of the deuteron and the reverse reaction of proton–proton fusion. The latter reaction cannot be directly measured, but is a crucial input into the stellar models. Extending this program to heavier nuclei would quickly get impractical because of the need to introduce three- and four-body forces and multiple counter terms.

Another interesting neutrino–nucleus reaction is the coherent elastic neutrino scattering off nuclei, $\nu + A \to \nu + A$. This is a Standard Model process, but only recently has been observed [13].

Neutrino–nucleus coherent elastic scattering differential cross section is given by [14]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T}(E_\nu, T) = \frac{G_F^2}{8\pi} M \left[2 - \frac{2T}{T_{\max}} + \left(\frac{T}{E_\nu}\right)^2 \right] Q_W^2 \left[F\left(Q^2\right)\right]^2 , \qquad (1)$$

where E_ν is the energy of the incoming neutrino, M and T are the mass and the recoil energy of the target nucleus, respectively. $T_{\max}$ is the maximum value of T. The weak charge of the nucleus,

$$Q_{\mathrm{W}} = N - \left(1 - 4\sin^2\theta_{\mathrm{W}}\right) Z\,,$$

primarily receives contributions from neutrons since $\sin^2\theta_{\mathrm{W}} \sim 1/4$. The form factor $F(Q^2)$, which is a function of the momentum transfer Q, corrects for contributions to scattering that are not completely coherent as E_ν gets large. Contributions of the neutron density to this form factor is dominant since the proton density is again suppressed because of the smallness of the factor $4\sin^2\theta_{\mathrm{W}} - 1$. Indeed, this reaction was proposed as a tool to measure neutron densities inside nuclei [15, 16]. It can also be useful in supernova detection [17]. Coherent elastic scattering of solar and atmospheric neutrinos is the background for the experiments searching for particle dark matter by measuring the recoil of target nuclei after they are struck by dark matter particles.

Integration of Eq. (1) over nuclear recoil energies yields the total elastic cross section. If one ignores the nuclear form factor (*i.e.*, $F(Q^2) = 1$), this yields $\sigma \propto E_\nu^2$ as expected. However, inclusion of nuclear structure effects reduces the cross section from this maximal value. Hence, a careful calculation of the nuclear structure effects is important if one wants to use this process as a probe to explore other physics such as the flux loss due to active-sterile neutrino mixing [18].

One should mention that there are also subdominant contributions to the coherent elastic neutrino–nucleus cross section such as those coming from non-zero neutrino magnetic moments. In a minimally extended Standard Model, these contributions are expected to be finite, but very small. However, new physics beyond the Standard Model may substantially increase them [19].

Most of the carbon in organic scintillators is in the form of ^{12}C. Since the natural abundance of ^{13}C is 1.07%, a sizable detector would already contain a substantial amount of this isotope. SFO Hamiltonian, enhancing monopole terms of the matrix elements in the $p_{1/2}$ and $p_{3/2}$ orbitals, includes tensor components consistent with the general sign rule for the tensor-monopole terms [20–22]. A persistent problem for weak interactions in nuclei is the need to quench the axial-vector coupling strength g_{A}. Part of this quenching comes from the limited size of the model space and the effective interactions used. Calculations with this Hamiltonian reproduces the measured neutrino–^{12}C cross sections with a reduced quenching of g_{A}, as compared to the previous calculations [23]. These cross sections at the reactor energies are calculated in Ref. [24]. It was found that using a configuration space including up to $2\hbar\omega$ interactions with a small (five percent)

quenching of the g_A and spin g factor, this Hamiltonian considerably improves the cross sections as compared with the earlier treatments using the Cohen–Kurath interactions [25].

3. Reactor neutrino flux

Short-baseline reactor neutrino experiments successfully measured the neutrino parameters they set out to measure, but they also identified a shape distortion in the 5–7 MeV range as well as a reduction from the predicted value of the flux [2]. This result and some of the other anomalies observed in neutrino experiments can be interpreted as mixing of sterile neutrinos with active ones [26]. It was argued that there exists a discrepancy in reactor neutrino experiments between observed antineutrino fluxes near the reactor core and the predicted values [27]. This anomaly can be fitted with additional sterile neutrino states.

Sterile neutrino explanation of the reactor flux discrepancy is not a universally agreed conclusion [28]. A careful analysis concludes that the corrections that lead to the reactor antineutrino anomaly are uncertain for the 30% of the flux that arises from forbidden decays [29]. Very recently, the flux of neutrinos coming from the fissions of ^{235}U and ^{239}Pu in the cores of Daya Bay reactors was measured [30] and was found to be about 5% less than predictions of the models [31, 32]. This result suggests that the main contribution to the deficit may be coming from the ^{235}U fission. Uncertainties in the subdominant corrections to beta decay dominate the reactor neutrino spectra [33], the resolution of which would require measuring fission products of many isotopes [34]. For example, three beta decays ^{92}Rb, ^{96}Y, and ^{142}Cs contribute 43% of the antineutrino flux emitted by nuclear reactors near 5.5 MeV. The latest measurement of these beta decays substantially modifies the feedings of ^{142}Ba from ^{142}Cs decays, increasing the discrepancy between the observed and the expected reactor antineutrino flux between 5 and 7 MeV [35]. One way to estimate the reactor neutrino spectra is first to measure electron spectra from thermal fission products and convert that to neutrino spectra. In this method, many fission products are measured together in a single experiment. It was pointed out [34] that including a shape correction of about $+6\%$ MeV^{-1} in conversion calculations fits the experimental Daya Bay spectrum better.

The ultimate resolution of this issue from the neutrino side lies in further experiments as one needs to precisely measure any relative distortion of the $\bar{\nu}_e$ spectrum as a function of both energy and baseline. PROSPECT, a precision oscillation and spectrum experiment, located at the High Flux Isotope Reactor (HFIR) at ORNL will measure the antineutrinos from a research reactor at a distance of less than 10 m to resolve these questions [36]. There are other experimental efforts with similar goals. NEOS exper-

iment already reported a negative result, significantly shrinking the sterile neutrino parameter space [37]. DANSS experiment also reported preliminary results [38]. Other experiments are in progress include STEREO [39] and SoLid [40] experiments. From the nuclear side, more input would be needed towards the solution of this puzzle. Indeed, recent experimental and theoretical developments point out to some issue with the normalization of the ^{235}U fission beta spectra measured several decades ago [41]. Normalization of this data relies not only on the U and Pu fission yields, but also on the neutron capture cross sections, particularly on the Au, Pb, Cd, and In isotopes. One could also envision measuring precise electron spectra of 50 or so fission products that can contribute. The shape factors for at least some of these can, in principle, be explored in rare ion facilities such as the Facility for Rare Ion Beams.

4. Experimental outlook

Recent developments with experimental techniques made it possible to measure charge-exchange reactions with unprecedented precision. This development enables nuclear experimentalists to make a very precise determination of the Gamow–Teller strength distributions. For example, the rate of the reaction ^{71}Ga(ν_e, e^-) was recently deduced from the $(^3$He,$t)$ charge-exchange reaction, leading to a slight change in the capture rate of the solar neutrinos coming from the *pp* reaction [42].

Direct measurements of neutrino–nucleus cross sections are possible with intense neutrino sources. For relatively low energies, aside from nuclear power reactors, the list of such sources may include spallation neutron sources and beta-beam facilities. In spallation neutron sources, one can obtain a rather intense neutrino flux. Pulsed nature of this neutrino flux can then be used to eliminate much of the background [44]. Indeed, such a facility was recently used to measure the coherent elastic neutrino–nucleus scattering [13]. Beta-beam facilities were proposed some time ago, but they are not currently under consideration. In such facilities, beta decay of boosted radioactive nuclei can be used to obtain an intense, collimated and pure neutrino beam. For low-energy neutrino–nucleus cross-section measurements, one can either use a low-energy beta beam [45] or utilize lower energy neutrinos at off-axis from a high-energy beta beam [46].

REFERENCES

[1] F.P. An *et al.* [Daya Bay Collaboration], *Chin. Phys. C* **41**, 013002 (2017) [`arXiv:1607.05378 [hep-ex]`].

[2] F.P. An *et al.* [Daya Bay Collaboration], *Phys. Rev. Lett.* **116**, 061801 (2016) [*Erratum ibid.* **118**, 099902 (2017)] [`arXiv:1508.04233 [hep-ex]`].

[3] Y. Abe *et al.* [Double Chooz Collaboration], *J. High Energy Phys.* **1601**, 163 (2016).

[4] J.H. Choi *et al.* [RENO Collaboration], *Phys. Rev. Lett.* **116**, 211801 (2016).

[5] L. Alvarez-Ruso *et al.*, `arXiv:1706.03621 [hep-ph]`.

[6] M. Butler, J.W. Chen, *Nucl. Phys. A* **675**, 575 (2000) [`arXiv:nucl-th/9905059`].

[7] M. Butler, J.W. Chen, X. Kong, *Phys. Rev. C* **63**, 035501 (2001) [`arXiv:nucl-th/0008032`].

[8] M. Butler, J.W. Chen, P. Vogel, *Phys. Lett. B* **549**, 26 (2002) [`arXiv:nucl-th/0206026`].

[9] J.W. Chen, K.M. Heeger, R.G.H. Robertson, *Phys. Rev. C* **67**, 025801 (2003) [`arXiv:nucl-th/0210073`].

[10] A.B. Balantekin, H. Yuksel, *Phys. Rev. C* **68**, 055801 (2003) [`arXiv:hep-ph/0307227`].

[11] A.B. Balantekin, H. Yuksel, *Int. J. Mod. Phys. E* **14**, 39 (2005) [`arXiv:nucl-th/0411025`].

[12] P.E. Shanahan *et al.*, *Phys. Rev. Lett.* **119**, 062003 (2017) [`arXiv:1701.03456 [hep-lat]`].

[13] D. Akimov *et al.* [COHERENT Collaboration], *Science* **357**, 1123 (2017) [`arXiv:1708.01294 [nucl-ex]`].

[14] D.Z. Freedman, D.N. Schramm, D.L. Tubbs, *Annu. Rev. Nucl. Part. Sci.* **27**, 167 (1977).

[15] K. Patton *et al.*, *Phys. Rev. C* **86**, 024612 (2012) [`arXiv:1207.0693 [nucl-th]`].

[16] K.M. Patton, G.C. McLaughlin, K. Scholberg, *Int. J. Mod. Phys. E* **22**, 1330013 (2013).

[17] C.J. Horowitz, K.J. Coakley, D.N. McKinsey, *Phys. Rev. D* **68**, 023005 (2003) [`arXiv:astro-ph/0302071`].

[18] A.J. Anderson *et al.*, *Phys. Rev. D* **86**, 013004 (2012) [`arXiv:1201.3805 [hep-ph]`].

[19] A.B. Balantekin, N. Vassh, *Phys. Rev. D* **89**, 073013 (2014) [`arXiv:1312.6858 [hep-ph]`].

[20] T. Suzuki, R. Fujimoto, T. Otsuka, *Phys. Rev. C* **67**, 044302 (2003).

[21] T. Otsuka *et al.*, *Phys. Rev. Lett.* **95**, 232502 (2005).

[22] T. Suzuki *et al.*, *Prog. Part. Nucl. Phys.* **59**, 486 (2007).

[23] T. Suzuki *et al.*, *Phys. Rev. C* **74**, 034307 (2006) [`arXiv:nucl-th/0608056`].

[24] T. Suzuki, A.B. Balantekin, T. Kajino, *Phys. Rev. C* **86**, 015502 (2012) [`arXiv:1204.4231 [nucl-th]`].

[25] M. Fukugita *et al.*, *Phys. Rev. C* **41**, 1359 (1990); M. Pourkaviani, S.L. Mintz, *J. Phys. G* **17**, 1139 (1991); S.L. Mintz, *Nucl. Phys. A* **672**, 503 (2000).

[26] K.N. Abazajian *et al.*, `arXiv:1204.5379 [hep-ph]`.

[27] G. Mention *et al.*, *Phys. Rev. D* **83**, 073006 (2011) [`arXiv:1101.2755 [hep-ex]`].

[28] A.B. Balantekin, *Eur. Phys. J. A* **52**, 341 (2016).

[29] A.C. Hayes *et al.*, *Phys. Rev. Lett.* **112**, 202501 (2014) [`arXiv:1309.4146 [nucl-th]`].

[30] F.P. An *et al.* [Daya Bay Collaboration], *Phys. Rev. Lett.* **118**, 251801 (2017) [`arXiv:1704.01082 [hep-ex]`].

[31] P. Huber, *Phys. Rev. C* **84**, 024617 (2011) [*Erratum ibid.* **85**, 029901 (2012)] [`arXiv:1106.0687 [hep-ph]`].

[32] T.A. Mueller *et al.*, *Phys. Rev. C* **83**, 054615 (2011) [`arXiv:1101.2663 [hep-ex]`].

[33] A.C. Hayes, P. Vogel, *Annu. Rev. Nucl. Part. Sci.* **66**, 219 (2016) [`arXiv:1605.02047 [hep-ph]`].

[34] A.A. Sonzogni, E.A. McCutchan, A.C. Hayes, *Phys. Rev. Lett.* **119**, 112501 (2017).

[35] B.C. Rasco *et al.*, *Phys. Rev. Lett.* **117**, 092501 (2016).

[36] J. Ashenfelter *et al.* [PROSPECT Collaboration], *J. Phys. G* **43**, 113001 (2016) [`arXiv:1512.02202 [physics.ins-det]`].

[37] Y.J. Ko *et al.*, *Phys. Rev. Lett.* **118**, 121802 (2017).

[38] I. Alekseev *et al.*, *J. Phys.: Conf. Ser.* **798**, 012152 (2017).

[39] J. Haser, `arXiv:1710.06310 [hep-ex]`.

[40] L. Manzanillas, arXiv:1710.07933 [physics.ins-det].

[41] K. Schreckenbach *et al.*, *Phys. Lett. B* **160**, 325 (1985).

[42] D. Frekers *et al.*, *Phys. Rev. C* **91**, 034608 (2015).

[43] S.J. Freeman *et al.*, *Phys. Rev. C* **96**, 054325 (2017) [`arXiv:1710.10817 [nucl-ex]`].

[44] A. Bolozdynya *et al.*, `arXiv:1211.5199 [hep-ex]`.

[45] C. Volpe, *J. Phys. G* **30**, L1 (2004) [`arXiv:hep-ph/0303222`].

[46] R. Lazauskas *et al.*, *Phys. Rev. D* **76**, 053006 (2007) [`arXiv:hep-ph/0703063`].