Elementary amplitudes from and for neutrino interactions

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neutrino oscillation experiment is **simple in conception**: 

![Graph showing neutrino oscillation probabilities](image)

but **difficult in practice**: rely on theory to determine cross sections: e.g. $\sigma(\nu_e)/\sigma(\nu_\mu)$ to a precision of 1%
**ν_e appearance from a ν_μ beam**

neutrino oscillation experiment is **simple in conception**:

![Graph showing ν_μ CC spectrum with oscillation probabilities for different CP violation and normal hierarchy values.]

but **difficult in practice**: rely on theory to determine cross sections: e.g. \( \sigma(\nu_e)/\sigma(\nu_\mu) \) to a precision of 1%
neutrino oscillation experiment is **simple in conception**: [Diagram of neutrino oscillation]

**v_e appearance from a ν_μ beam**

Do it as a function of energy

Measure fraction of ν_e appearing in ν_μ beam

but **difficult in practice**: rely on theory to determine cross sections: e.g. \( \sigma(v_e)/\sigma(v_\mu) \) to a precision of 1%
Important questions in the 3 flavor paradigm

- limits on achievable precision due to neutrino interaction uncertainties

\[
\delta \sigma_{\text{CCQE}} \lesssim 5\% \implies \sim 7k \text{ CCQE events}
\]

\[
\delta \sigma_{\text{CCQE}} \lesssim 1\% \implies \sim 170k \text{ CCQE events}
\]

current knowledge of nucleon level CCQE cross section based on \(~3.5k\) events

\[
\sigma_{\nu n \to \mu p}(E_\nu = 1 \text{ GeV}) = 10.1(0.9) \times 10^{-39} \text{ cm}^2
\]

\[
\sigma_{\nu n \to \mu p}(E_\nu = 3 \text{ GeV}) = 9.6(0.9) \times 10^{-39} \text{ cm}^2
\]
Important questions beyond the 3 flavor paradigm

- short baseline anomalies

SM backgrounds to MiniBooNE excess

In the MiniBooNE detector, CC signal degenerate with NC single photon background

kinematic shape of the excess looks similar to single photon background
this background is estimated using a resonance insertion approach

At the nucleon level, 12 invariant amplitudes depending on 3 kinematic invariants (cf. CCQE: 1 poorly known amplitude \( F_A \) depending on 1 invariant \( Q^2 \))

Background looks like signal, is hard to calculate, and has never been measured. (!)

Nucleon level needed to validate MiniBooNE pion-based estimate, and to relate MiniBooNE/MicroBooNE

\[
\delta \sigma_{1\gamma} \lesssim 100 \% \quad \Rightarrow \quad \mathcal{O}(1k) \text{ CCQE events}
\]

\[
\delta \sigma_{1\gamma} \lesssim 10 \% \quad \Rightarrow \quad \mathcal{O}(100k) \text{ CCQE events}
\]

( based on counting statistics, \( \sigma_{1\gamma} \sim O(10^{-3}) \sigma_{\text{CCQE}} \) )
Important questions beyond neutrinos

- **BSM signals and constraints beyond neutrinos**

\[ V_{ud} \text{ and CKM unitarity} \]

A key radiative correction to neutron and nuclear beta decay is sensitive to nucleon structure

Recent reanalysis of this correction implies > 4\(\sigma\) violation of CKM unitarity

\[
|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9983(4)
\]

*Seng, Gorchtein, Patel, Ramsey-Musolf, 1807.10197*
Inaccessible to electron scattering, but related (via isospin) to forward neutrino scattering and (via dispersion relation) to neutrino-nucleon cross sections.

Available data is limited by statistics and impacted by nuclear effects.

Moment of inelastic structure function

box correction related to integral of this function, needed to 1% precision

\[ \Box_{W}^{VA} = \frac{3\alpha}{16\pi} \int_0^{\infty} \frac{dQ^2}{Q^2} \frac{M_W^2}{M_W^2 + Q^2} M_3^{(0)}(1, Q^2). \]
Important questions beyond neutrinos

• precision measurements

\( r_A \) puzzle

Aside: can we phrase the neutrino-nucleus scattering problem in standard form?

1) identify a finite set of physical quantities that determine the problem

2) constrain these numbers by any and all means

3) propagate uncertainties to interesting quantities, like fundamental neutrino parameters

We’re still trying to arrive at this standard form. Regardless, \( r_A \) is likely to be in the final set.
A critical number: the nucleon axial radius

quasi elastic (QE) dominance

nucleon form factors for QE process

linear dependence of form factors on kinematics
What do we know about this critical number?

The number seemed uncontroversial for decades:

*extracted from deuterium bubble chamber data*

Kitigaki et al. PRD 28, 436 (1983)
What do we know about this critical number?

In fact the extraction relied on a hidden model assumption, and the true uncertainty is an order of magnitude larger

*Bhattacharya, RJH, Paz 2011*

*Meyer, Betancourt, Gran, RJH 2016*

*Introduces a $\geq 10\%$ uncertainty in every neutrino-nucleus cross section. A wrench in the works for oscillation experiments.*
What do we know about this critical number?

Look at the process in reverse: muon capture from ground state of muonic hydrogen

Improved theory analysis and existing data: already competitive with world ν-d data. Significant improvements possible

*RJH, Kammel, Marciano, Sirlin 2017*
What do we know about this critical number?

Lattice QCD is also embarking on an ambitious, long-range program to answer this challenge

~5σ discrepancy between blue point and black points
Complementarity between $r_A$ constraints from different processes

$r_A$ from neutrino data, and/or lattice QCD $\Rightarrow$ muon capture provides a stringent test of muon versus electron universality

current : $\delta(r_A^2) = 50\%$
Complementarity between $r_A$ constraints from different processes

Figure 5: (color online) Relation between $g_A$ and $r_A^2$ from electron and muon processes. The black band shows $g_A$ from neutron decay (Table 2). The green band denotes the $g_A r_A^2$ region consistent with the present MuCap result within 1-sigma, the yellow band the potential of a future 3-times improved measurement (the same central value has been assumed). The current value and uncertainty in $r_A^2$ from the neutrino scattering analysis is shown by vertical lines. If $r_A^2$ would be known to 1%, the future experiment would determine $g_A$ within the red region.

We should note, however, that a recent trapped neutron lifetime experiment at Los Alamos\cite{96} with very small systematic uncertainties finds $\tau_n = 877.7(7)\text{ s}$, in strong support of earlier trapped neutron results. Roughly estimating the effect of the new result on the neutron lifetime average suggests a preliminary average $\tau_{\text{ave}} = 879.3(9)\text{ s}$. This shorter average lifetime leads to a larger $g_A = 1.2749(9)$, based on the PDG value for $\tau_n$ and $V_{ud}$ given in Table 2. We should note, however, that a recent trapped neutron lifetime experiment at Los Alamos\cite{96} with very small systematic uncertainties finds $\tau_n = 877.7(7)\text{ s}$, in strong support of earlier trapped neutron results. Roughly estimating the effect of the new result on the neutron lifetime average suggests a preliminary average $\tau_{\text{ave}} = 879.3(9)\text{ s}$. This shorter average lifetime leads to a larger $g_A = 1.2749(9)$, based on the PDG value for $\tau_n$ and $V_{ud}$ given in Table 2. We should note, however, that a recent trapped neutron lifetime experiment at Los Alamos\cite{96} with very small systematic uncertainties finds $\tau_n = 877.7(7)\text{ s}$, in strong support of earlier trapped neutron results. Roughly estimating the effect of the new result on the neutron lifetime average suggests a preliminary average $\tau_{\text{ave}} = 879.3(9)\text{ s}$. This shorter average lifetime leads to a larger $g_A = 1.2749(9)$, based on the PDG value for $\tau_n$ and $V_{ud}$ given in Table 2.

For now, the value of $r_A^2$ obtained from the $z$ expansion fit to neutrino-nucleon quasi-elastic scattering together with the MuCap singlet muonic Hydrogen capture rate $\mu_{\text{singlet}}$ can be used in Eq. (25) to obtain a muon based value, $g_A = 1.276(8) r_A^2(8)_{\text{MuCap}} = 1.276(11)$. That overall roughly $\pm 1\%$ sensitivity is to be compared with the current, better than $\pm 0.1\%$, determination of $g_A$ from the electron based neutron lifetime that we have been using in our text, or the preliminary update including Ref.\cite{96} given above.

The good agreement can be viewed as a test of electron-muon universality in semileptonic charged current interactions at roughly the 1% level. We have described how a factor of 3 improvement in the MuCap $\mu_{\text{singlet}}$ provides a stringent test of muon versus electron universality current: $\delta(r_A^2) = 50\%$

e.g. $\delta(r_A^2) = 10\% \implies \sim 30k$ CCQE events
a smattering of topics needing more precise elementary amplitude input:
(certainly not exhaustive)

● nucleon level CCQE cross section
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● MiniBooNE excess
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● neutron beta decay and CKM unitarity
\[ \delta \Box = 1\% \implies \sim \mathcal{O}(10 - 100k) \text{ events} \]

● \( r_A \) for muon capture and mu-e universality
\[ \delta (r_A^2) = 10\% \implies \sim 30k \text{ CCQE events} \]

● …
Workshop in summer 2018 at Seattle INT featured a focused discussion on the question of elementary amplitudes

http://www.int.washington.edu/PROGRAMS/18-2a/18-2a_workshop.html

organizers M. Betancourt, RJH, S. Pastore

A report is in progress, not restricted to workshop participants (rjh@fnal.gov)

The following is a selective summary of the workshop discussion.

(In what follows, parenthetical talk references refer to other talks at the INT link above. There are many relevant talks here at PONDD, I will not attempt to list them all.)
• definition of elementary amplitude
  
  • $F_A$ (too narrow)
  
  • $S$ matrix elements at the nucleon level: $vN \rightarrow \ell N$, $eN \rightarrow eN$, $N \rightarrow N\pi$, $N \rightarrow X$, $NN \rightarrow NN$, etc.
  
  • inputs to nuclear modeling
  
  • the initio of ab initio
  
  • any physical quantity that lattice QCD can measure involving one or a few nucleons
  
  • any physical quantity that can be measured in an elementary target (H or D) scattering experiment
• the questions

(1) what do we know?

(2) what do we need to know?

(3) how can we come to know it?

All questions are difficult, but after normalization, (1)=(3)=easy, (2)=hard
discussion and report on elementary amplitudes

• motivations

  • well defined quantities
  
  • important component of the error budget
  
  • necessary to inform and discriminate nuclear models
  
  • important, fruitful, interesting intersections (lattice, e-p, muonic atoms, ...)
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Probably not enough, but serious attempts to quantify

(talks of Meyer, Morfin, Ruso, Sato, Wilkinson)

- challenges from low statistics and limited data preservation

- open questions on deuteron corrections
• the questions

(1) what do we know?

(2) what do we need to know?

(3) how can we come to know it?

New elementary target data (Bross, Kammel)
- underground safety raises the bar for making the physics case
- what can be achieved by subtraction methods using compound targets?

Precision lattice QCD (talks of Kronfeld, Lin, Shanahan)
- $F_A$ within sight
- complementary to scattering data

Electron and positron beams (Crawford, Nakamura), muonic atoms (Kammel), ...

Many elements of the physics case (question 2) are common between these paths. Practitioners have strategic interest in helping make this physics case.
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(1) what do we know?

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(3) how can we come to know it?

Three levels (at least) of answer

(i) regardless of nuclear model, nucleon-level data tests critical elements of oscillation analyses (e.g. disentangling differences in $\nu_\mu/\nu_e$ from radiative corrections and detector response) (McFarland)

(ii) propagate elementary input errors through a/the default nuclear model and oscillation analysis. Need those errors to be smaller than the desired precision on fundamental neutrino parameters.

(Ashkenazi, Castillo, Himmel, Mahn, Ruterbories)
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Three levels (at least) of answer

(iii) the whole shebang

A complete and quantitative answer requires a complete and quantitative nuclear model.

- need to break the circle: improving nuclear models requires better knowledge of the nucleon level amplitudes.
• the questions

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Three levels (at least) of answer

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• closing thoughts

- our knowledge of elementary amplitudes is rudimentary

- our ignorance impacts neutrino and non-neutrino processes, long and short baseline, SM measurements and BSM searches, quasielastic and inelastic scattering

- difficult but important measurements are obvious targets at future neutrino facilities
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THANKS!