Understanding supernova $\nu_e$ detection with MARLEY

Steven Gardiner

Precision Investigations of the Neutrino Sector

17 July 2019

Precision Investigations of the Neutrino Sector

SLAC National Accelerator Laboratory, July 14-17, 2019

Fermilab
Supernova 1987A

- 25 antineutrinos detected in 13 s
- Only experimental observation to date
- Three detectors involved
  - Kamiokande-II (WC)
  - Irvine-Michigan-Brookhaven (WC)
  - Baksan underground scintillation telescope (liquid scintillator)
- Confirmed basic picture of core-collapse SN
- A high-statistics SN measurement would be exciting
  - Core-collapse dynamics & nucleosynthesis
  - Neutrinos under extreme conditions
  - Exotic physics searches
- Complementary to gravitational wave and optical observations
**A “wish list” for a supernova neutrino detector**

<table>
<thead>
<tr>
<th>Detector requirement</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large mass (~ktons)</td>
<td>Enough statistics</td>
</tr>
<tr>
<td>Low energy threshold (few MeV)</td>
<td>Detection of the low E SN neutrino spectra</td>
</tr>
<tr>
<td>Sensitivity to different neutrino flavors</td>
<td>Distinguish different SN effects and neutrino oscillations</td>
</tr>
<tr>
<td>Good knowledge of low-E cross sections and neutrino interactions (particle ID)</td>
<td>Tag different interactions</td>
</tr>
<tr>
<td>Accurate neutrino energy reconstruction</td>
<td>SN features</td>
</tr>
<tr>
<td>Good timing resolution</td>
<td>SN features</td>
</tr>
<tr>
<td>Good angular resolution</td>
<td>SN direction</td>
</tr>
<tr>
<td>Separation from backgrounds</td>
<td>Identification of SN signal</td>
</tr>
<tr>
<td>Good trigger efficiency/DAQ</td>
<td>Large data acquisition in a few seconds</td>
</tr>
</tbody>
</table>

Challenging to do all of this with just one!
All have a role to play in maximizing the physics potential of the next supernova observation

In this talk, however, I’ll focus on argon, using water for contrast
# Supernova-relevant neutrino interactions

<table>
<thead>
<tr>
<th>Charged current</th>
<th>Neutral current</th>
<th>Nuclei</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrons</strong></td>
<td><strong>Protons</strong></td>
<td><strong>Nuclei</strong></td>
</tr>
<tr>
<td>Elastic scattering</td>
<td>Inverse beta decay</td>
<td>$\nu_e + (N, Z) \rightarrow e^- + (N - 1, Z + 1)$</td>
</tr>
<tr>
<td>$\nu + e^- \rightarrow \nu + e^-$</td>
<td>$\bar{\nu}_e + p \rightarrow e^+ + n$</td>
<td>$\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N + 1, Z - 1)$</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>$\gamma$</td>
<td>Various possible ejecta and deexcitation products</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$e^+$</td>
<td></td>
</tr>
<tr>
<td>$e^-$</td>
<td>$\gamma$</td>
<td></td>
</tr>
<tr>
<td>Useful for pointing</td>
<td>Elastic scattering</td>
<td>$\nu + A \rightarrow \nu + A^*$</td>
</tr>
<tr>
<td>$\nu$</td>
<td>$p$</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>$\gamma$</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>$n$</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>$\gamma$</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>$A$</td>
<td>Coherent elastic (CEνNS)</td>
</tr>
</tbody>
</table>

IBD (electron antineutrinos) dominates for current detectors
# Supernova-relevant neutrino interactions

<table>
<thead>
<tr>
<th></th>
<th>Electrons</th>
<th>Protons</th>
<th>Nuclei</th>
</tr>
</thead>
</table>
| **Charged current** | Elastic scattering | Inverse beta decay | $\nu_e + (N, Z) \rightarrow e^- + (N - 1, Z + 1)$  
$\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N + 1, Z - 1)$ |
|                | $\nu + e^- \rightarrow \nu + e^-$ | $\bar{\nu}_e + p \rightarrow e^+ + n$ |
| ![Diagram of charged current interactions](image1.png) | ![Diagram of inverse beta decay](image2.png) |

<table>
<thead>
<tr>
<th><strong>Neutral current</strong></th>
<th>Elastic scattering</th>
<th>Nuclear reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Useful for pointing</td>
<td>Coherent elastic (CEvNS)</td>
</tr>
<tr>
<td></td>
<td>very low energy recoils</td>
<td>$\nu + A \rightarrow \nu + A^*$</td>
</tr>
<tr>
<td><img src="image3.png" alt="Diagram of neutral current interactions" /></td>
<td><img src="image4.png" alt="Diagram of nuclear reactions" /></td>
<td></td>
</tr>
</tbody>
</table>

Nuclear target needed to isolate electron neutrino flux!
Supernova neutrino detection with water Cherenkov detectors

- Pure water instrumented with photomultipliers
- Primary reaction mode: “inverse beta decay”
- Positron detected using Cherenkov radiation
- Tag neutron to discriminate against other reaction channels
  - Loading water with Gd improves efficiency

Reconstructing true antineutrino energy:

$$E_{\bar{\nu}} = E_e + \Delta + K_{\text{recoil}}$$

where:
- $E_{\bar{\nu}}$: antineutrino energy
- $E_e$: electron energy
- $\Delta$: neutron-proton mass difference
- $K_{\text{recoil}}$: recoil energy of neutron (negligible)
One of DUNE’s primary science goals is to measure “the $\nu_e$ flux from a core-collapse supernova within our galaxy, should one occur during the lifetime of the DUNE experiment” – DUNE CDR

- **Unique $\nu_e$ sensitivity**
  - Complementary to other SN neutrino detectors

- Other low-energy physics measurements may be possible (e.g., solar neutrinos)

- SN sensitivity is an important design consideration
Supernova neutrino detection in liquid argon

Charged-current absorption:
\[ \nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^- \]

At least 25 transitions have been observed indirectly

Transition levels are determined by observing de-excitations (γ’s and nucleons)

Transitions to particle-unbound levels occur with many competing de-excitation channels

Large uncertainties in nuclear data and models complicate energy reconstruction

Reconstructing true neutrino energy:

\[ Q \] is determined by measuring de-excitation gammas and nucleons

\[ E_\nu = E_e + Q + K_{\text{recoil}} \]

Outgoing e\(^-\) Energy
Energy donated to transition
Recoil Energy of Nucleus (negligible)
How do oscillation experiments handle this problem?

- Generators are an essential tool to help relate observed event topologies to the neutrino energy
  - Detailed simulations provide “fake data” used to understand energy resolution, efficiencies, etc.
  - Hard work to understand systematic errors

- GENIE, GiBUU, NEUT, and NuWro typically used at accelerator energies (100s of MeV and above)

- Standard physics treatment designed for these energies: what differences might be important for supernova neutrinos?
Can we play the same game for supernova neutrinos?

- Trouble starts when we consider how the physical picture changes for low energy neutrinos

- At high energies, neutrino-nucleus scattering is described as a **direct reaction**: the neutrino scatters on a single nucleon (or a pair of nucleons) inside the nucleus

"Traditional" factorization scheme for generators at accelerator energies
Can we play the same game for supernova neutrinos?

- At tens-of-MeV, on the other hand, compound reactions are thought to dominate

- These proceed via the formation of a thermally equilibrated excited nucleus, which then decays
  - For a ~10 MeV neutrino, even transitions to low-lying nuclear levels become important!

- The compound nucleus idea goes back to Niels Bohr in the 1930s

  “The first stage of [a nuclear] collision . . . consists in the formation of an intermediate semi-stable system composed of the original nucleus and the incident particle. The excess energy . . . [is] temporarily stored in some complicated motions of all the particles in the compound system.”

  “Its eventual disintegration must be considered as a separate event, independent of the first stage of the collision process.”
Have we seen evidence of compound reactions in lepton-nucleus scattering data?

- **Yes**, with electrons

- A good example can be seen in this measurement of the $^{60}\text{Ni}(e,\alpha)e'X$ reaction

- Compound nucleus model (solid line) works very well at 33 MeV

- High-energy tail attributable to direct reactions begins to appear at 60 MeV

- Obvious at 120 MeV

A. G. Flowers et al., PRL 40, 709–712 (1978)
MARLEY: Model of Argon Reaction Low-Energy Yields

- Event generator for supernova neutrinos on $^{40}\text{Ar}$
- Current version does CC $\nu_e$ (dominant channel)
- Framework allows adding new reactions, target nuclei, etc.
- Widely used by DUNE for supernova neutrino detection studies

Discussed in detail in my PhD thesis
MARLEY: Model of Argon Reaction Low-Energy Yields

- Written in modern C++, mostly from scratch

- ~10K lines of code

- Distributed independently and as part of the LArSoft framework used by many liquid argon neutrino experiments

MARLEY command-line executable running natively on my Kindle Paperwhite
MARLEY event generation flowchart

Enter event loop

**Initialize generator**
- Define reactions / matrix elements
- Load nuclear data
- Weight incident spectrum with cross section

**Event is complete**

Re-enter event loop

$^{40}\text{Ar}(\nu_e, e^-)^{40}\text{K}^*$ cross section model

**2-2 scatter**
- Sample reacting neutrino energy
- Sample $^{40}\text{K}$ level
- Sample electron direction

Is the current level...

- the ground state?
- nucleon unbound?
- a bound excited state?

Sample new level using Hauser-Feshbach model

Sample new level using $\gamma$ tables

Produce de-excitation products

Nuclear de-excitation model
How can we calculate the loading of the nuclear levels?
Weak–nuclear interaction

\[ \nu_e + A(Z, N) \Rightarrow A^\ast (Z + 1, N - 1) + e^- \]

\[ \bar{\nu}_e + A(Z, N) \Rightarrow A^\ast (Z - 1, N + 1) + e^+ \]

(i) O’Connell, Donnelly & Walecka, PR6, 719 (1972)
(ii) Kuramoto et al. NPA 512, 711 (1990)
(iii) Luyten et al. NP41, 236 (1963)

ALL ARE EQUIVALENTS.
MARLEY $^{40}$Ar($\nu_e$, e$^-$)$^{40}$K* cross section model

- Under the allowed approximation, the differential cross section for a particular nuclear level is given by

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2 |V_{ud}|^2}{4\pi^2} p_e |E_e| F(Z_f, E_e) \times \left[ (1 + \beta_e \cos \theta_e) B(F) + \left( \frac{3 - \beta_e \cos \theta_e}{3} \right) B(GT) \right]$$

- MARLEY uses tabulated B(F) and B(GT) values to compute cross sections.

- The NUCLEARREACTION class samples two-two scattering final states using this cross section:
  1. $^{40}$K* excited level
  2. e$^-$ energy
  3. e$^-$ direction

- De-excitation of the final nucleus is simulated next.

Integrated Gamow-Teller Strength for CC $\nu_e$ on $^{40}$Ar
MARLEY $^{40}\text{Ar}(\nu_e, \text{e}^-)^{40}\text{K}^*$ cross section model

Fermi matrix element comes from time component of nuclear operator

$$B(F) \equiv g_V^2 \left| \left\langle f \left| \sum_{k=1}^{A} \tau_-(k) \right| i \right\rangle \right|^2$$

Gamow-Teller matrix element comes from spatial components

$$B(GT) \equiv g_A^2 \left| \left\langle f \left| \sum_{k=1}^{A} \sigma(k) \tau_-(k) \right| i \right\rangle \right|^2$$

Fermi transition is well-understood

Gamow-Teller less so...
Sources of B(GT) data for $^{40}$Ar

Measurements using (p,n) scattering vs. $^{40}$Ti beta decay show significant disagreements.

Assumptions must be made to extract B(GT) values either way.

MARLEY chooses to remain agnostic and provides 3 datasets (A, B, C).

Must be supplemented by theory at higher energies.

---

PHYSICAL REVIEW C 80, 055501 (2009)

Weak-interaction strength from charge-exchange reactions versus $\beta$ decay in the $A = 40$ isoquintet

M. Bhattacharya,1,2,* C. D. Goodman,2 and A. García3

---

![Graph showing B(GT) vs. $^{40}$K $E_x$ (MeV)]
How can we simulate the nuclear de-excitation?
MARLEY de-excitation model: bound states

- If the residual nucleus is in a bound state, then tables of discrete γ-ray branching ratios are used to repeatedly sample transitions down to the ground state.

- These tables are largely taken from a compilation provided with version 1.6 of the TALYS nuclear code.
  - Some updates have been made to $^{40}$K based on the latest (2017) ENSDF evaluation for $A = 40$.

FIG. 1. Level scheme of $^{40}$Ar-$^{40}$K relevant to $\nu_e$ capture in argon.

R. Raghavan (1986)
MARLEY de-excitation model: unbound states

- If the residual nucleus is in an unbound state, an exit channel is sampled using decay widths from the Hauser-Feshbach statistical model
  - If excitation energy remains, another de-excitation step is taken afterwards
  - Only binary decays are taken into account by the model

**Hauser-Feshbach model**

- Relies on the compound nucleus assumption
- Partial decay widths depend on
  - Initial level $E_x$ and $J^\pi$
  - Discrete levels
  - Continuum level density
  - Transmission coefficients
Hauser-Feshbach Model

W. Hauser and H. Feshbach, Physical Review 87, 366 (1952)

- Commonly used for modeling low-energy nuclear cross sections
- Two key assumptions:
  1. compound nucleus
  2. reciprocity theorem (time-reversal invariance)

- Transmission coefficient $T_{\ell,j} = \text{probability for fragment to escape the nucleus}$
- Compound nucleus + time-reversal symmetry = $T_{\ell,j}$ via “reciprocity”
- Optical model is used to compute $T_{\ell,j}$ for time-reversed process
- Numerical solution of Schrödinger equation via Numerov’s method

The fragment emission width of a compound nucleus

$A \rightarrow \alpha + B$

is related to its formation cross section

$\alpha + B \rightarrow A$
Hauser-Feshbach Model

W. Hauser and H. Feshbach, Physical Review 87, 366 (1952)

- Commonly used for modeling low-energy nuclear cross sections

- Two key assumptions:
  1. compound nucleus
  2. reciprocity theorem (time-reversal invariance)

\[
\Gamma_{A\rightarrow\alpha+B} = \frac{1}{2\pi \rho_A(E_x, J, \Pi)} \sum_{\ell', j'} \int \delta_\pi \rho_B(E'_x, I', \Pi') T_{\ell', j'}(\epsilon) d\epsilon
\]

Parity conservation

\[
\delta_\pi = \begin{cases} 
1 & \Pi = \pi_{\alpha} \Pi'(1)^{\ell'} \\
0 & \text{otherwise}
\end{cases}
\]

Monte Carlo implementation

\[
P(A \rightarrow \alpha + B) = \frac{\Gamma_{A\rightarrow\alpha+B}}{\Gamma_A}
\]
CC total cross section

- Similar to existing theoretical calculations, some much more detailed but not data-driven

- Appears to give reasonable results even above the ~50 MeV threshold where forbidden terms become significant
Exclusive cross sections

Similar treatment to that used in arXiv:nucl-th/0311022 for $^\text{16}\text{O}$

$X\gamma$ means “any number of gammas”

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{total}$</td>
<td>black</td>
</tr>
<tr>
<td>$^{40}\text{Ar}(\nu_e, e^- X\gamma)^{40}\text{K}$</td>
<td>blue</td>
</tr>
<tr>
<td>$^{40}\text{Ar}(\nu_e, e^- n X\gamma)^{39}\text{K}$</td>
<td>red</td>
</tr>
<tr>
<td>$^{40}\text{Ar}(\nu_e, e^- p X\gamma)^{39}\text{Ar}$</td>
<td>brown</td>
</tr>
<tr>
<td>$^{40}\text{Ar}(\nu_e, e^- \alpha X\gamma)^{36}\text{Cl}$</td>
<td>green</td>
</tr>
<tr>
<td>$^{40}\text{Ar}(\nu_e, e^- 2n X\gamma)^{38}\text{K}$</td>
<td>orange</td>
</tr>
<tr>
<td>$^{40}\text{Ar}(\nu_e, e^- np X\gamma)^{38}\text{Ar}$</td>
<td>purple</td>
</tr>
<tr>
<td>$^{40}\text{Ar}(\nu_e, e^- 2p X\gamma)^{38}\text{Cl}$</td>
<td>cyan</td>
</tr>
</tbody>
</table>
Higher neutron emission in particular leads to big spectral distortions!

40K* de-excitations
- $\gamma$s only: 82.3%
- single n + $\gamma$s: 12.7%
- single p + $\gamma$s: 3.3%
- other: 1.7%

40K* de-excitations
- $\gamma$s only: 60.7%
- single n + $\gamma$s: 25.6%
- single p + $\gamma$s: 8.3%
- other: 5.3%
Example $e^- + \gamma$s Only Event (true trajectories)

- $E_\nu = 16.1$ MeV
- $e^-$ deposited $10.2$ MeV
- $\gamma$s deposited $4.3$ MeV
- $^{40}$K deposited $3.7$ keV
- Total visible energy: $14.5$ MeV
- Visible energy sphere radius: $48.4$ cm
Example $e^- + \gamma s$ Only Event (cheated reco)

- $E_\nu = 16.1$ MeV
- $e^-$ deposited 10.2 MeV
- $\gamma$s deposited 4.3 MeV
- $^{40}K$ deposited 3.7 keV
- Total visible energy: 14.5 MeV
- Visible energy sphere radius: 48.4 cm
Example neutron event (true trajectories)

- $E_\nu = 16.3 \text{ MeV}$
- $e^- \text{ deposited } 4.5 \text{ MeV}$
- $^{39}\text{K} \text{ deposited } 68 \text{ keV}$
- $n \text{ deposited } 7.6 \text{ MeV}$ (mostly from capture $\gamma$s)
- Total visible energy: 12.2 MeV
- Visible energy sphere radius: 1.44 m
Example neutron event (cheated reco)

- $E_\nu = 16.3$ MeV
- $e^-$ deposited 4.5 MeV
- $^{39}\text{K}$ deposited 68 keV
- n deposited 7.6 MeV (mostly from capture $\gamma$s)

- Total visible energy: 12.2 MeV
- Visible energy sphere radius: 1.44 m
DUNE’s use of MARLEY

- A variety of low-energy studies for DUNE are underway using MARLEY

- The examples shown here are from D. Pershey’s May 2019 DUNE collaboration meeting talk

- Double peak in the bottom plot
  - Right peak: $e + \gamma$ only
  - Left peak: neutron emission!
Improving MARLEY: more detailed cross section model

- Recent work by the U. Ghent group ([arxiv 1903.07726](https://arxiv.org/abs/1903.07726)) has shown the importance of higher-order multipoles to low-energy neutrino cross sections

- Contributions become important around ~40 MeV

- They’re working with me to get their calculation into MARLEY
  - More strength to high-lying states
  - New channels (e.g., NC)

- Full impact of the physics improvements on DUNE observables remains to be seen

- Stay tuned!
The higher order multipoles give significant strength for low outgoing lepton energies
Improving MARLEY: constraining the models

Decay-at-rest near NuMI target hall

C. Grant and B. Littlejohn, arXiv:1510.08431

Opportunities With Decay-At-Rest Neutrinos From Decay-In-Flight Neutrino Beams

Christopher Grant
Physics Department, University of California, Davis, CA 95616, USA
Bryce Littlejohn
Physics Department, Illinois Institute of Technology, Chicago, IL 60616, USA
(Dated: November 6, 2015)

Neutrino beams from spallation neutron facilities can produce copious quantities of neutrinos from the decay at rest of mesons and muons. A viability of decay-in-flight neutrino beams as sites for decay-at-rest neutrino studies has been investigated by calculating expected low-energy neutrino fluxes from the existing Fermilab NuMI beam facility. Decay-at-rest neutrino production in NuMI was found to be roughly equivalent per megawatt to that of spallation facilities, and is concentrated in the facility’s target hall and beam stop regions. Interaction rates in 5 and 60 ton liquid argon detectors at a variety of existing and hypothetical locations along the beamline are found to be comparable to the largest existing decay-at-rest datasets for some channels. The physics implications and experimental challenges of such a measurement are discussed, along with prospects for measurements at targeted facilities along a future Fermilab long-baseline neutrino beam.

Flux is within a factor two of SNS within same detector stand-off distance. Backgrounds also need to be determined!

- **Muon decay-at-rest** $v_e$ provide the most direct route to constraining MARLEY’s cross section models
- Possible sites for such a measurement include
  - Spallation Neutron Source @ Oak Ridge
  - Near NuMI target hall @ Fermilab
- Discussed by C. Grant at the last PINS

<table>
<thead>
<tr>
<th>Model</th>
<th>Fiducial events / $10^{20}$ POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>QRPA</td>
<td>10.4</td>
</tr>
<tr>
<td>RQRPA</td>
<td>20.0</td>
</tr>
<tr>
<td>PQRPA</td>
<td>23.4</td>
</tr>
<tr>
<td>MARLEY v1.1.0 dataset A</td>
<td>28.6</td>
</tr>
<tr>
<td>RPA</td>
<td>29.4</td>
</tr>
<tr>
<td>GTBD</td>
<td>33.0</td>
</tr>
<tr>
<td>“Hybrid” shell model + RPA</td>
<td>38.6</td>
</tr>
</tbody>
</table>
Improving MARLEY: constraining the models

- **MicroBooNE** has demonstrated reconstruction of electrons in the relevant energy range (from muon decays)

- Using the flux estimate from arXiv:1510.08431, here is the predicted event rate
  - **Not great, but it’s something**
  - Note the large theory uncertainty

- A dedicated experiment could achieve far higher statistics and a high impact for DUNE

Predicted µDAR $\nu_e$ fiducial event rate (truth) in MicroBooNE for $E_{\nu_e} \geq 10$ MeV

<table>
<thead>
<tr>
<th>Model</th>
<th>Fiducial events / $10^{20}$ POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>QRPA</td>
<td>10.4</td>
</tr>
<tr>
<td>RQRPA</td>
<td>20.0</td>
</tr>
<tr>
<td>PQRPA</td>
<td>23.4</td>
</tr>
<tr>
<td>MARLEY v1.1.0 dataset A</td>
<td>28.6</td>
</tr>
<tr>
<td>RPA</td>
<td>29.4</td>
</tr>
<tr>
<td>GTBD</td>
<td>33.0</td>
</tr>
<tr>
<td>“Hybrid” shell model + RPA</td>
<td>38.6</td>
</tr>
</tbody>
</table>
Improving MARLEY: constraining the models

• **COHERENT** is pursuing a number of useful cross section measurements in this energy range

• Using a theory calculation for the different targets for which data are expected soon (e.g., Pb, I), their data could help constrain MARLEY’s general approach

• Other indirect methods could also be helpful (e.g., muon capture on $^{40}$Ar)
Conclusion

• Through its enhanced sensitivity to $\nu_e$, a large liquid argon detector like DUNE can provide a valuable window into the complex physics of supernovae.

• Despite this great potential, modeling neutrino-argon scattering at tens-of-MeV is **complicated**
  - Cross section remains completely unmeasured!

• Just like oscillation measurements, interpretation of SN $\nu_e$ data in $^{40}$Ar will require the use of a generator.

• **MARLEY represents a first step in this direction**, with more theory engagement and constraining measurements to come!
Backup
Example proton event (true trajectories)

- $E_\nu = 17.8$ MeV
- $e^{-}$ deposited 1.9 MeV
- $\gamma$ deposited 1.3 MeV
- $^{39}$Ar deposited 170 keV
- $p$ deposited 5.4 MeV
- Total visible energy: 8.7 MeV
- Visible energy sphere radius: 34 cm
- Protons leave a “stub” on the electron track
- Big error on $E_\nu$ if you miss them!
Example proton event (cheated reco)

- $E_\nu = 17.8$ MeV
- $e^-$ deposited 1.9 MeV
- $\gamma$ deposited 1.3 MeV
- $^{39}$Ar deposited 170 keV
- $p$ deposited 5.4 MeV
- Total visible energy: 8.7 MeV
- Visible energy sphere radius: 34 cm
- Protons leave a “stub” on the electron track
- Big error on $E_\nu$ if you miss them!
For low-energy CC scattering on a free nucleon, the amplitude may be written as

\[ i\mathcal{M} = -i \frac{G_F V_{ud}}{\sqrt{2}} \ell_\mu n_\mu \]

\[ n_\mu = \chi^\dagger_{N_f} \bar{u}_{N_f} (p_{N_f}) \left[ \gamma^\mu F_1(Q^2) + \frac{i}{2m_N} \sigma^{\mu\nu} q_\nu F_2(Q^2) - \gamma^\mu \gamma^5 G_A(Q^2) - \frac{q_\mu}{m_N} \gamma^5 G_P(Q^2) \right] \tau_- u_{N_i} (p_{N_i}) \chi_{N_i} \]
MARLEY $^{40}$Ar($\nu_e$, e$^-$)$^{40}$K* cross section model

Let’s rewrite the nucleon matrix element in terms of a current operator:

$$n^\mu = \langle N_f | \hat{j}^\mu | N_i \rangle$$

$$\hat{j}^0 \propto \left( F_1(Q^2) + \frac{(p_{N_i} + q) \cdot \sigma}{E_{N_i} + m_N + q^0} \left[ \frac{q \cdot \sigma}{2m_N} F_2(Q^2) - G_A(Q^2) + \frac{q^0}{m_N} G_P(Q^2) \right] \right)$$

$$- \left[ \frac{q \cdot \sigma}{2m_N} F_2(Q^2) - G_A(Q^2) - \frac{q^0}{m_N} G_P(Q^2) \right] \frac{p_{N_i} \cdot \sigma}{E_{N_i} + m_N}$$

$$+ \frac{(p_{N_i} + q) \cdot \sigma}{E_{N_i} + m_N + q^0} F_1(Q^2) \frac{p_{N_i} \cdot \sigma}{E_{N_i} + m_N} \tau_-$$

(similar long expression for spatial components)
A sum over nucleons is used to evaluate the nuclear operator

\[
i \mathcal{M} = -i \frac{G_F V_{ud}}{\sqrt{2}} \ell_\mu \mathcal{N}^\mu
\]

\[
\mathcal{N}^\mu \equiv \langle f | \hat{\mathcal{N}}^\mu | i \rangle \quad \hat{\mathcal{N}}^\mu \approx \sum_{k=1}^{A} e^{i \mathbf{q} \cdot \mathbf{x}_k} \hat{j}_\mu (k)
\]

Exponential comes from switch to position space
MARLEY transmission coefficient model

- Level densities are calculated using the BACKSHIFTEDFERMIGASMODEL with global fit parameters from Koning, et al. (2008)

\[
\rho_{\text{BFGM}}(E_x, J, \Pi) = \frac{\sqrt{\pi}}{24} \left[ \frac{2J+1}{2\sqrt{2\pi}\sigma^3} \right] \left[ \frac{\exp(2\sqrt{aU})}{a^{1/4}U^{5/4}} \right] \exp \left[ -\frac{(J + \frac{1}{2})^2}{2\sigma^2} \right]
\]

- Gamma transmission coefficients use the STANDARDLORENTZIANMODEL and global giant resonance fits from RIPL

- Nuclear fragment transmission coefficients are calculated using the global optical potential of Koning & Delaroche (KONINGDELA ROCHEOPTICALMODEL)


\[
\mathcal{U} = \mathcal{V}_V + i\mathcal{W}_V + i\mathcal{W}_D + \mathcal{V}_{SO} + i\mathcal{W}_{SO} + \mathcal{V}_C
\]

\[
\left[ \frac{d^2}{dr^2} - \frac{\ell'(\ell' + 1)}{r^2} + k^2 - \frac{2\mu}{\hbar^2}\mathcal{U} \right] u_{\ell'j'}(r) = 0
\]

- Solve radial Schrödinger equation numerically in matching region

\[
\lim_{r \to \infty} u_{\ell'j'}(r) = \frac{i}{2} \left[ H_{-\ell'}^{-}(k, r) - S_{\ell'j'} H_{+\ell'}^{+}(k, r) \right]
\]

- Match to asymptotic solution, extract transmission coefficient

\[
T_{\ell'j'} = 1 - |S_{\ell'j'}|^2
\]

Transmission coefficient represents the probability of penetrating the nuclear surface.
How does MARLEY create events?

- The user describes the incident spectrum, the reaction matrix elements, etc. in a configuration file.
- Based on the incident spectrum and the reaction cross section(s), MARLEY creates a probability density function for sampling *reacting* neutrinos.

- A rejection technique is used to sample a reacting neutrino energy.
- If multiple reactions are defined, MARLEY selects one using the cross sections as weights.
Putting all of the pieces together gives us the following differential cross section for a particular nuclear level:

$$
\frac{d\sigma}{d\Omega} = \frac{G_F^2 |V_{ud}|^2}{4\pi^2} |p_e| E_e F(Z_f, E_e) \times \left[ (1 + \beta_e \cos \theta_e)B(F) + \left( \frac{3 - \beta_e \cos \theta_e}{3} \right) B(GT) \right]
$$

Calculating the cross section is straightforward if we can figure out the nuclear matrix elements $B(F)$ and $B(GT)$

There are two relevant experiments in the literature. Both are indirect measurements.
Neutrino absorption efficiency of an $^{40}\text{Ar}$ detector from the $\beta$ decay of $^{40}\text{Ti}$

M. Bhattacharya, A. García, and N. I. Kaloskamis*
University of Notre Dame, Notre Dame, Indiana 46556

E. G. Adelberger and H. E. Swanson
University of Washington, Seattle, Washington 98195

R. Anne, M. Lewitowicz, M. G. Saint-Laurent, and W. Trinder
GANIL, BP 5027, F-14021 Caen Cedex, France

Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay Cedex, France
(Received 4 August 1998)

Make 40-Ti via heavy ions on a thin, heavy target (e.g. Cr on Ni). Embed ions in silicon detector.

Use TOF and dE/dx to separate 40-Ti out from ion "soup"

Observe beta decay to 40-Sc excited states, which decay via delayed proton emission
$^{40}\text{Sc}^*$ levels were found using the proton energy

\[ E_x = E_{p}^{\text{lab}} + \begin{cases} 589 \text{ keV} & \text{p}_0 \\ 3060 \text{ keV} & \text{p}_1 \end{cases} \]

- 21 p$_0$ and 7 p$_1$ decays were observed