Status of Neutrino Cross Sections

Sam Zeller
Fermilab
U Pittsburgh Workshop
December 6, 2012

• what we know and don’t know

• will point out well-known neutrino processes that can be used for flux determinations in neutrino experiments
Neutrino Cross Sections

CC $\nu$-nucleon cross sections:

![Graph showing neutrino cross sections](image)

- $E_{\nu}$ (GeV) on the x-axis
- Cross section $\times 10^{-38} \text{ cm}^2 / \text{GeV}$ on the y-axis

Key points:
- 100 MeV
- 300 GeV
- QE, DIS, RES contributions
- TOTAL cross section

S. Zeller, UPitt workshop 12/06/12
Neutrino Cross Sections

CC $\nu$-nucleon cross sections:

- cross sections typically well known at very low energies
  - *IBD (10’s MeV)*
  - *solar $\nu$’s*
- and at very high energies
  - *DIS (100’s GeV)*
- but not so well-known in the middle (100’s MeV – 10’s GeV)
Neutrino Cross Sections

CC $\nu$-nucleon cross sections:

- Cross sections typically well known at very low energies
  - $IBD$ (10’s MeV)
  - $DIS$ (100’s GeV)

- Not so well-known in the middle (100’s MeV – 10’s GeV)

- This intermediate $E$ region is important because this is where we’re conducting our $\nu$ oscillation experiments ($MH, CP$)
Complicated Region

(event samples contain contributions from multiple reaction mechanisms)

-neutrino

CC Quasi-elastic
nucleon changes, but doesn't break up

CC Single pion
nucleon excites to resonance state

CC Deep Inelastic
nucleon breaks up

T2K
NOvA
CNGS
LBNE
atmospheric
• $\sigma_\nu$’s are not particularly well-constrained in this intermediate E region
  (situation is embarrassingly worse for NC and for $\bar{\nu}$)

... the situation has been improving
(with the availability of new higher statistics data)
Neutrino QE Scattering

Why important?

- important for $\nu$ oscillation experiments
  - typically gives largest contribution to signal samples in many osc exps

examples:

$\nu_\mu \rightarrow \nu_e$ ($\nu_e$ appearance)
$\nu_\mu \rightarrow \nu_X$ ($\nu_\mu$ disappearance)

- biggest piece of the $\sigma$ at ~1 GeV
  (lepton kinematics are used to infer $E_\nu$)

(typically thought of as a process with a single knock-out nucleon)

(heavily studied in 1970’s and 80’s, one of the 1st $\nu$ interactions measured)
Neutrino QE Scattering

(see Laura’s talk!)
Neutrino QE Scattering

* be careful (re: QE selection and use of $E_\nu$)! 

(see Laura’s talk!)
Neutrino QE Scattering

- first time we’ve had enough stats to measure double diff’l dists

- example: QE data from MiniBooNE
  - Nieves, Simo, Vacas, PL B707, 72 (2012)
Neutrino QE Scattering

- QE scattering is a great example of how we shouldn’t assume that $\nu$ cross sections are well in hand (even “simple” ones)

  *MiniBooNE data is the 1st time have measured the $\nu$ QE $\sigma$ on a nuclear target below 2 GeV*

- $\sigma$’s are appreciably larger than conventional approaches 
  *(also K2K, MINOS, SciBooNE)*

- there are other nuclear effects in play (MEC, np-nh)? idea is not new: *theory papers in 1990’s + also seen in e-nucleus QE scattering*

(L. Alvarez-Ruso, NuFact11)
Theory Side

- this is something that needs to get sorted out and people are working hard on this …

- Lalakulich, Mosel, arXiv:1208.3678
- Bodek et al., arXiv:1207.1247
- Ankowski, PRC 86, 024616 (2012)
- Butkevich, arXiv:1204.3160
- Lalakulich et al., arXiv:1203.2935
- Mosel, arXiv:1204.2269, 1111.1732
- Barbaro et al., arXiv:1110.4739
- Giusti et al., arXiv:1110.4005
- Meloni et al., arXiv:1203.3335, 1110.1004
- Paz, arXiv:1109.5708
- Sobczyk, arXiv:1201.3673, 1109.1081, 1201.3673
- Nieves et al., PRD 85, 113008 (2012), 1106.5374, 1110.1200, PRC 83, 045501 (2011)
- Bodek et al., arXiv:1106.0340
- Antonov, et al., arXiv:1104.0125
- Benhar, et al., arXiv:1012.2032, 1103.0987, 1110.1835
- Alvarez-Ruso, arXiv:1012.3871

• over 50 theory papers on the topic of ν QE in the past year!
Implications

• neutrino-nucleus QE scattering is not a “standard candle”
  - could be missing a sizable contrib to $\sigma$ in our simulations ($\sim 40\%$ at 1 GeV)
  - additional measurements are crucial to fully understand & model the underlying physics (MINER$\nu$A, LAr TPCs)

• why you should care:
  (1) impacts $E_\nu$ determination
    ex: Mosel/Lalakulich 1204.2269, Martini et al. 1202.4745, Lalakulich et al. 1203.2935, Leitner/Mosel PRC81, 064614 (2010)
  (2) effects will be different for $\nu$ vs. $\bar{\nu}$
    (at worse, could produce a spurious $CP$ effect)

has direct implications on neutrino oscillation experiments

(see Jorge and Debbie’s talks)
Single Pion Production

- as we move up in energy, resonance production starts to dominate
  – this is a large source of pion production in neutrino interactions

\[ \text{example: } \nu_\mu p \rightarrow \mu^- \Delta^{++} \rightarrow p \pi^+ \]

(such baryonic resonances can also decay to multi-\(\pi\), other mesons, and even \(\gamma\)'s)

- \(1\pi\) production is the one that has been most-well measured
Single Pion Production

- a new appreciation for nuclear effects in this region as well
- FSI change f.s. particle composition and kinematics (these can be large effects!)

(ex. pion charge exchange)

- effects what you observe experimentally (can only detect what exits the target nucleus)
One Example: CC $\pi$ Production

- cross section for CC $\nu$ interactions producing a single $\pi$ exiting nucleus (measures initial interaction $\times$ nuclear effects $\times$ FSI)

- recent $\pi$ production measurements on nuclear targets also from K2K, SciBooNE, and NOMAD
One Example: CC $\pi$ Production

- cross section for CC $\nu$ interactions producing a single $\pi$ exiting nucleus (measures initial interaction x nuclear effects x FSI)

- recent $\pi$ production measurements on nuclear targets also from K2K, SciBooNE, and NOMAD

- best meas of initial interaction $\sigma$ come from ANL, BNL ($D_2$); even these differ by $\sim20\%$ from each other

- $\nu$-induced single $\pi$ production is not a "standard candle" either
Multi-Pion Production

- only existing measurements of multi-$\pi$ production come from $D_2$-based bubble chamber measurements (contain contributions from both RES & DIS)

- we’re in for a bit of trouble here - multi-$\pi$ production is one of the largest contributing processes in LBNE (MINER$\nu$A can help!)

- multi-$\pi$ production is not a “standard candle”

Rev. Mod. Phys. 84, 1307 (2012)
Total CC Inclusive ($\nu_\mu N$)

\[ \sigma_{CC} / E_v \left(10^{-38} \text{ cm}^2 / \text{GeV}\right) \]

\[ \nu_\mu N \rightarrow \mu^- X \]

\[ \overline{\nu}_\mu N \rightarrow \mu^+ X \]

\begin{itemize}
  \item ANL, PRD 19, 2521 (1979)
  \item ArgoNeuT, arXiv:1111.0103 [hep-ex]
  \item BEBC, ZP C2, 187 (1979)
  \item BNL, PRD 25, 617 (1982)
  \item BNL-E0639 CRS, PRL 44, 916 (1980)
  \item CCFR (1997 Seligman Thesis)
  \item CDHS, ZP C35, 443 (1987)
  \item GGM-SPS, PL 104B, 235 (1981)
  \item GGM-PS, PL 84B (1979)
  \item IHEP-ITEP, SJNP 30, 527 (1979)
  \item IHEP-JINR, ZP C70, 39 (1996)
  \item MINOS, PRD 81, 072002 (2010)
  \item NOMAD, PLB 660, 19 (2008)
  \item NuTeV, PRD 74, 012008 (2006)
  \item SciBooNE, PRD 83, 012005 (2011)
  \item SKAT, PL 81B, 255 (1979)
\end{itemize}
Total CC Inclusive ($\nu_\mu N$)
Total CC Inclusive ($\nu_\mu N$)

- used to help set $\Phi_\nu$ predictions in expts like BEBC, SKAT, Serpukhov, and K2K, MINOS, NOMAD

This is the region we care about for accel-based oscillation experiments.
\( \nu_e \) Cross Sections

- \( \nu_e \) cross section measurements are much harder to come by especially at GeV energies (in accelerator sources, we intentionally reduce \( \nu_e \)'s in our beams)
- existing \( \nu_e, \bar{\nu}_e \) cross section measurements are limited to decay-at-rest, radiological, and reactor sources ... all at very low energies

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Reaction Channel</th>
<th>Source</th>
<th>Experiment</th>
<th>Measurement (10^{-42} cm²)</th>
<th>Theory (10^{-42} cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{2}H)</td>
<td>(^{3}H(\nu_e, e^-)pp)</td>
<td>Stopped ( \pi/\mu )</td>
<td>LAMPF</td>
<td>52 ± 18 (tot)</td>
<td>54 (LA) (Tatara et al., 1990)</td>
</tr>
<tr>
<td>(^{12}C)</td>
<td>(^{12}C(\nu_e, e^-)^{12}N_{e}^{+})</td>
<td>Stopped ( \pi/\mu )</td>
<td>KARMEN</td>
<td>9.1 ± 0.5(stat) ± 0.8(sys)</td>
<td>9.4 [Multipole] (Donnelly and Peccei, 1979)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stopped ( \pi/\mu )</td>
<td>E225</td>
<td>10.5 ± 1.0(stat) ± 1.0(sys)</td>
<td>9.2 [EPT] (Fukugita et al., 1988)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stopped ( \pi/\mu )</td>
<td>LSND</td>
<td>8.9 ± 0.3(stat) ± 0.9(sys)</td>
<td>8.9 [CRPA] (Kolbe et al., 1999b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stopped ( \pi/\mu )</td>
<td>KARMEN</td>
<td>5.1 ± 0.6(stat) ± 0.5(sys)</td>
<td>5.4-5.5 [CRPA] (Kolbe et al., 1999b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stopped ( \pi/\mu )</td>
<td>E225</td>
<td>3.6 ± 2.0 (tot)</td>
<td>4.1 [Shell] (Hayes and S, 2000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stopped ( \pi/\mu )</td>
<td>LSND</td>
<td>4.3 ± 0.4(stat) ± 0.6(sys)</td>
<td></td>
</tr>
<tr>
<td>(^{56}Fe)</td>
<td>(^{56}Fe(\nu_e, e^-)^{56}Co)</td>
<td>Stopped ( \pi/\mu )</td>
<td>KARMEN</td>
<td>256 ± 108(stat) ± 43(sys)</td>
<td>264 [Shell] (Kolbe et al., 1999b)</td>
</tr>
<tr>
<td>(^{71}Ga)</td>
<td>(^{71}Ga(\nu_e, e^-)^{71}Ge)</td>
<td>(^{53}Cr) source</td>
<td>GALLEX, ave.</td>
<td>0.0054 ± 0.0009 (tot)</td>
<td>0.0068 [Shell] (Haxton, 1998)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^{53}Cr)</td>
<td>SAGE</td>
<td>0.0055 ± 0.0007 (tot)</td>
<td>0.0070 [Shell] (Bahcall, 1997)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^{35}Ar) source</td>
<td>SAGE</td>
<td>0.0055 ± 0.0006 (tot)</td>
<td></td>
</tr>
<tr>
<td>(^{127}I)</td>
<td>(^{127}I(\nu_e, e^-)^{127}Xe)</td>
<td>Stopped ( \pi/\mu )</td>
<td>LSND</td>
<td>284 ± 9(stat) ± 25(sys)</td>
<td>210-310 [Quasi-particle] (Engel et al., 1994)</td>
</tr>
</tbody>
</table>

\(< 50 \text{ MeV}\)

\(\sim 700 \text{ keV}\)

Rev. Mod. Phys. 84, 1307 (2012)

- need a higher energy, well-known \( \nu_e \) source: \( \nu \)STORM!
What We Know and Don’t Know

• spent a lot of time talking about things we don’t know very well:
  - nuclear effects in $\nu$ QE scattering
  - final state effects in resonant $\pi$ production
  - $\nu_e$ cross sections, etc.

• this intermediate E range (~0.1-10 GeV) remains a challenge
  (new data telling us that things are more complex than we may have thought)
  - not a lot of processes we can anchor to
    with well-known (few-%) $\sigma$’s

• so what do we know?
  - look back in history at some of the “standard candles”
    $\nu$ experiments used to determine their $\nu$ fluxes
• neutrino experiments measure the product of flux x cross section:

\[ N_\nu = \Phi_\nu \times \sigma_\nu \times \varepsilon \]

• so if can identify an event sample with a well-known cross section, can in principle, measure your \( \nu \) flux to some high degree of precision:

\[ \Phi_\nu = \frac{N_\nu}{\sigma_\nu \times \varepsilon} \]

• historically, there are a lot of examples of this, at least in the cases where can find out how the experiment determined their \( \nu \) flux

(this information is often hard to find)
Summary of $\Phi_\nu$ Methods in QE Experiments

### Table 2: Summary of analysis techniques employed in the experimental study of neutrino quasi-elastic (QE) scattering

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Selection</th>
<th>Number of events</th>
<th>QE purity</th>
<th>Flux (reference)</th>
<th>$M_A$</th>
<th>$F_\nu(Q^2)$</th>
<th>$\sigma(E_\nu)$</th>
<th>$\frac{d\sigma}{dQ^2}$</th>
<th>$\frac{d^2\sigma}{dT_\nu d\theta_\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANL</td>
<td>Two- and three-track</td>
<td>1,737</td>
<td>98%</td>
<td>Hadro (14)</td>
<td>√</td>
<td>—</td>
<td>√</td>
<td>√</td>
<td>—</td>
</tr>
<tr>
<td>BEBC</td>
<td>Three-track</td>
<td>552</td>
<td>90%</td>
<td>$\nu_\mu$ CC (15)</td>
<td>√</td>
<td>—</td>
<td>√</td>
<td>√</td>
<td>—</td>
</tr>
<tr>
<td>BNL</td>
<td>$\nu$: three-track &amp; one-track</td>
<td>$\nu$: 1,138</td>
<td>$\nu$: 97%</td>
<td>$\nu_\mu$ QE (49)</td>
<td>√</td>
<td>—</td>
<td>√</td>
<td>√</td>
<td>—</td>
</tr>
<tr>
<td>FNAL</td>
<td>$\nu$: two- and three-track &amp; one-track</td>
<td>$\nu$: 362</td>
<td>$\nu$: 97%</td>
<td>$\nu_\mu$ QE (56)</td>
<td>√</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>GGM</td>
<td>$\nu$: two-track &amp; one-track</td>
<td>$\nu$: 337</td>
<td>$\nu$: 97%</td>
<td>Hadro (31)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>—</td>
</tr>
<tr>
<td>Serpukhov</td>
<td>One-track</td>
<td>$\nu$: 757</td>
<td>$\nu$: 51%</td>
<td>Hadro, $\nu_\mu$ CC (19)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>SKAT</td>
<td>$\nu$: two-track &amp; one-track</td>
<td>$\nu$: 540</td>
<td>—</td>
<td>$\nu_\mu$ CC (20)</td>
<td>√</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>K2K</td>
<td>One- and two-track</td>
<td>5,568</td>
<td>62%</td>
<td>Hadro, $\nu_\mu$ CC (52)</td>
<td>√</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>One-track</td>
<td>146,070</td>
<td>77%</td>
<td>Hadro (53)</td>
<td>√</td>
<td>—</td>
<td>√</td>
<td>√</td>
<td>—</td>
</tr>
<tr>
<td>SciBooNE (preliminary)</td>
<td>One- and two-track</td>
<td>16,501</td>
<td>67%</td>
<td>Hadro (53)</td>
<td>—</td>
<td>—</td>
<td>√</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>MINOS (preliminary)</td>
<td>One-track</td>
<td>345,000</td>
<td>61%</td>
<td>$\nu_\mu$ CC (27)</td>
<td>√</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>NOMAD</td>
<td>$\nu$: one- and two-track &amp; one-track</td>
<td>$\nu$: 14,021</td>
<td>$\nu$: 42%</td>
<td>Hadro, DIS, IMD (7)</td>
<td>√</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Abbreviations: CC, charged-current; DIS, deep-inelastic scattering; hadro, hadro-production; IMD, inverse muon decay.

Summary of $\Phi_\nu$ Methods in QE Experiments

- **QE** (BNL, FNAL)
- **hadro-production** (ANL, GGM, MB, SB)
- **total CC** (BEBC, Serpukhov, SKAT, K2K, MINOS, NOMAD)
- **IMD** (NOMAD)

First Neutrino Experiments

• early experiments (1970’s, 1980’s) had more faith in their neutrino cross section predictions than their flux estimates

  - $\nu_\mu$ QE scattering considered a “standard candle”

• QE was a common sample used to determine the flux normalization in many of the first neutrino experiments

  “the absolute normalization of the flux can be calculated from the theoretical expressions if one knows $M_A$”

  (FNAL 15-ft bubble chamber)

• BTW, this led to some unfortunate circularity in a few experiments

  - same data used to determine the $\nu$ flux and later the $\sigma_{QE}$

  - this is something we need to be careful about today too!
Gargamelle

- one of the earliest examples I could find …

- 236 $\nu_\mu$ QE events on freon

- $M_A = 1.0 \pm 0.35$ GeV ($Q^2$ fit)

“Fig. 6 shows the energy distribution of the neutrino flux up to 4 GeV derived from the elastic event rate and cross section computed for $M_A = 1.0$ GeV. Except at low energy, it is consistent with the flux calculated by Van der Meer on the basis of measured pion and kaon production spectra.”

(M. Block et al., PL 12, 281, 1964)
Deuterium

• $\nu_\mu$ QE scattering on $D_2$ was process of choice for the flux determination in many early $\nu$ experiments:

\[ \nu_\mu \ g d \rightarrow \mu^- \ p \ p_S \]

• nuclear effects are small and calculable (Singh, NP B36, 419, 1972)

• vector form factors from $e^-$

• get $M_A$ from $Q^2$ shape fit to $\nu$ QE ("independent of absolute flux normalization")

(S.J. Barish et al., PRD 16, 11, 1977)
Deuterium

$\nu_\mu$ QE scattering on $D_2$ was process of choice for the flux determination in many early $\nu$ experiments:

- nuclear effects are small and calculable (Singh, NP B36, 419, 1972)
- vector form factors from $e^-$
- get $M_A$ from $Q^2$ shape fit to $\nu$ QE ("independent of absolute flux normalization")

S. Zeller, UPitt workshop 12/06/12
Neutrino Flux and Total Charged-Current Cross Sections in High-Energy Neutrino-Deuterium Interactions

T. Kitagaki, S. Tanaka, H. Yuta, K. Abe, K. Hasegawa, A. Yamaguc
T. Hayashino, Y. Ohtani, and H. Hayano
Tohoku University, Sendai 980, Japan

To obtain the total cross section from the number of events, the neutrino flux has to be measured on an absolute scale. In this analysis, we determine the neutrino flux using 362 quasielastic events identified in our data$^{10}$ and the cross section for reaction (2) derived from the $V-A$ theory.

measured $\nu$ flux = $(6.15 \pm 0.36) \times 10^{14} \, \nu/m^2$

prediction = $3.62 \times 10^{14} \, \nu/m^2$

$\times 1.7$ difference

FIG. 2. Neutrino flux distribution obtained from the quasielastic events and the predicted cross section with $M_A = 1.05 \, \text{GeV}$. The solid curve is obtained from the best fit to the flux data for $E_\nu > 30 \, \text{GeV}$. The dashed curve is taken from the Monte Carlo simulation of the flux.
High-energy quasielastic $\nu_\mu n \rightarrow \mu^- p$ scattering in deuterium

T. Kitagaki, S. Tanaka, H. Yuta, K. Abe, K. Hasegawa,
A. Yamaguchi, K. Tamai, T. Hayashino, Y. Otani, H. Hayano, and H. Sagawa
Tohoku University, Sendai 980, Japan

R. A. Burnstein, J. Hanlon, and H. A. Rubin
Illinois Institute of Technology, Chicago, Illinois 60616

C. Y. Chang, S. Kunori, G. A. Snow, D. Son, P. H. Steinberg, and D. Zieminska
University of Maryland, College Park, Maryland 20742

R. Engelmann, T. Kafka, and S. Sommers
State University of New York at Stony Brook, Stony Brook, New York 11794

C. C. Chang, W. A. Mann, A. Napier, and J. Schneps
Tufts University, Medford, Massachusetts 02155
(Received 13 December 1982)

We have studied the quasielastic reaction $\nu_\mu n \rightarrow \mu^- p$ in an exposure of the Fermilab deuterium-filled 15-foot bubble chamber to a high-energy wide-band neutrino beam. From an analysis of the $Q^2$ distribution based on the standard $V-A$ theory, the axial-vector mass in a dipole parametrization of the axial-vector form factor is determined to be $M_A = 1.05 \pm 0.12$ GeV, consistent with the values previously reported from low-energy experiments.

- flux used to publish an absolute $\nu_\mu$ QE cross section (a bit of circularity here)
Determination of the neutrino fluxes in the Brookhaven wide-band beams


Physics Department, Brookhaven National Laboratory, Upton, New York 11973

• measured their $\nu_e$, $\overline{\nu}_\mu$, and $\nu_\mu$ flux using samples of QE events on $D_2$

FIG. 10. The measured flux $\phi(E(\nu_e))$ together with the calculated result of Fig. 14. The data have been adjusted by a factor of 1.1 consistent with the scale uncertainties in the data and Monte Carlo calculations.

FIG. 11. The measured flux $\phi(E(\nu_\mu))$ together with the calculated result of Fig. 13. The data have been adjusted by a factor of 1.3 consistent with the scale uncertainties in the data and Monte Carlo calculations.

FIG. 8. The measured flux $\phi(E(\nu_\mu))$ together with the calculated result of Fig. 12. The data have been adjusted by a factor of 1.1 consistent with the scale uncertainties in the data and Monte Carlo calculations. POT stands for protons incident on target.
Determination of the neutrino fluxes in the Brookhaven wide-band beams


Physics Department, Brookhaven National Laboratory, Upton, New York 11973

- measured their $\nu_e$, $\overline{\nu}_\mu$, and $\nu_\mu$ flux using samples of QE events on $D_2$

The beam calculations described here were based on the Grote, Hagedorn, and Ranft (GHR) (Ref. 11) parametrization; that of Sanford and Wang was used for comparison. An estimate was made of pion production by reinteracting protons guided by the shape of the observed $\nu_\mu$ spectrum and the observed angular distribution of muons from quasielastic events. The procedure is described$^{12}$ in the Appendix.

![Graph](image)

FIG. 8. The measured flux $\phi(E(\nu_\mu))$ together with the calculated result of Fig. 12. The data have been adjusted by a factor of 1.1 consistent with the scale uncertainties in the data and Monte Carlo calculations. POT stands for protons incident on target.
The beam targets of the Brookhaven target were parametrization; the beam parameter was $\sigma_{\nu}$ for comparison. An estimate of $\sigma_{\nu}$ was obtained by reinteracting experimentally determined $\nu_\mu$ events and measured $\nu_\mu$ spectrum from the observation of muons from quasilinear and elastic showers. The procedure is described in the Appendix.

To modify the production spectrum to fit the neutrino data, we multiplied the four $p_\pi$ parameters (1.18, 1.79, 1.24, 1.21 in order of $p_\pi$) and the modification is consistent with the effect expected from secondary interactions. We have calculated $\phi(E(\nu_\mu))$, $\phi(E(\nu_\tau))$, and $\phi(E(\nu_e))$ using the same $p_\pi$ parameters and the same $\sigma_{\nu}$.

**FIG. 8.** The measured flux $\phi(E(\nu_\mu))$ together with the calculated result of Fig. 12. The data have been adjusted by a factor of 1.1 consistent with the scale uncertainties in the data and Monte Carlo calculations. POT stands for protons incident on target.
• this is one case where the situation is clear

• neutrino QE cross sections are measured using a flux calculated from $\pi$ production data alone (and not $\nu$ QE)
Study of neutrino interactions in hydrogen and deuterium:
Description of the experiment and study of the reaction $\nu + d \rightarrow \mu^- + p + p_s$


Argonne National Laboratory, Argonne, Illinois 60439

VII. CHECK OF NEUTRINO FLUX FROM THE QUASIELASTIC SCATTERING EVENTS

The cross sections, shown in Fig. 22, are calculated using the flux measured from our pion production cross sections. If we assume a value for $M_A$, then we can, in turn, use the total cross-section data to measure the neutrino flux. Since $M_A$ can be measured from the shape of the $Q^2$ distribution only, this provides a useful independent measurement of the flux. The $M_A$ value we use is $M_A = 0.95$-GeV, our flux-independent result as given in Table IV, which is also consistent with values obtained by other neutrino experiments listed in Table V.
Study of neutrino interactions in hydrogen and deuterium:
Description of the experiment and study of the reaction $\nu + d \rightarrow \mu^- + p + p_s^+$


Argonne National Laboratory, Argonne, Illinois 60439

TABLE IV. Results of axial–form–factor fits.

<table>
<thead>
<tr>
<th>Likelihood function</th>
<th>$M_A^{\text{Dipole}}$ (GeV)</th>
<th>$M_A^{\text{Monopole}}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate</td>
<td>$0.75^{+0.13}_{-0.11}$</td>
<td>$0.45^{+0.14}_{-0.07}$</td>
</tr>
<tr>
<td>Shape</td>
<td>$1.010 \pm 0.09$</td>
<td>$0.56 \pm 0.08$</td>
</tr>
<tr>
<td>Rate and shape</td>
<td>$0.95 \pm 0.09$</td>
<td>$0.52 \pm 0.08$</td>
</tr>
<tr>
<td><strong>Flux independent</strong></td>
<td>$0.95 \pm 0.09$</td>
<td>$0.53 \pm 0.08$</td>
</tr>
</tbody>
</table>

Table V. **Our event numbers then give a flux that is 21% lower than that measured from our pion yields.**

(BTW: modern fit are about 25% lower than Cho fits)
Study of neutrino interactions in hydrogen and deuterium:
Description of the experiment and study of the reaction $\nu + d \rightarrow \mu^- + p + p_s$‡


Argonne National Laboratory, Argonne, Illinois 60439

A second technique which is completely independent of the form factors is to extrapolate the differential cross section to $Q^2 = 0$, where the cross section is given by

$$\frac{d\sigma}{dQ^2} \bigg|_{Q^2=0} = \frac{G^2 \cos^2 \theta}{2\pi} \left[ F_V(0)^2 + F_A(0)^2 \right]$$

$$= 1.98 \times 10^{-38} \text{ cm}^2/\text{GeV}^2.$$ 

Extrapolating the data of Fig. 23 to $Q^2 = 0$ also gives a flux that is 22% lower than shown in Fig. 8 in agreement with the previous method.

we’ll come back to this idea later

(BTW: modern fit are about 25% lower than Cho fits)
Standard Candles

• a lot of past experiments used QE scattering on D$_2$, so what are the “standard candle” $\nu$ interactions for modern LF experiments wishing to get a better handle on their flux?
  
  (i.e., what are the $\sigma_\nu$ that are well-known in this $E$ region, to a few %)?

• typically not $\nu$-nucleus scattering
  
  - not even QE, despite any temptations you might have from previous experimental techniques (unless H$_2$ or D$_2$)!

• what are some standard candle reactions in this E region?

  - neutrino-electron scattering ($\nu_\mu$ e$^- \rightarrow \mu^- \nu_e$)
  - DIS (low $\nu$ method)
  - $\nu$-deuterium QE scattering (in limit $Q^2 \rightarrow 0$)
  - certain nuclear transitions ($\nu_\mu ^{12}\text{C} \rightarrow \mu^- ^{12}\text{N}_{g.s.}$)
Neutrino-electron scattering

• purely-leptonic process, so $\sigma$ calculation is very straightforward (no strongly interacting particles involved!)

\[ \sigma = \frac{2G_F^2 m_e}{\pi} \left[ \left( g_L^2 + \frac{g_R^2}{3} \right) E_\nu - g_L g_R \frac{m_e}{2} \right] \]

$g_L = \sin^2 \theta_W \pm \frac{1}{2}$

$g_R = \sin^2 \theta_W$

• $\sigma$ is $\sim$ linear with $E_\nu$ (generic feature of point-like scattering)

• $\sigma$ is small: $\sigma \sim (E_{CM})^2 = 2M_{\text{target}} E_\nu$

• directional: $E_e \theta_e^2 < 2m_e$

• challenge is to get enough statistics

• and need good electron reconstruction

\[ \sim 4 \text{ orders of magnitude less likely than scattering off nucleons at } 1 \text{ GeV} \]

(see Jaewon's talk)
Inverse Muon Decay and DIS

• more commonly, experiments have used the CC version of this $\nu$-electron scattering process, IMD

$\nu_\mu \, e^- \rightarrow \mu^- \, \nu_e$

$\bar{\nu}_e \, e^- \rightarrow \mu^- \, \bar{\nu}_\mu$

• however, this can’t help you with $\bar{\nu}_\mu$ fluxes

• often combined with using DIS events (low $\nu$ method)

• both IMD and DIS require having higher energy events (see Arie’s talk)

- used for the $\Phi_\nu$ determination in $\nu$ experiments like NOMAD

IMD: $496 \pm 33$ events (7% flux constraint)

DIS (1.6% & 5.9% check in $\nu$ & $\bar{\nu}$)

• what about lower energy experiments? what can they use?
• there are certain nuclear transitions that have well-known cross sections

\[ \nu_{\mu}^{12}C \rightarrow \mu^{-}^{12}N_{\text{g.s.}} \]

\[ \downarrow \]

\[ ^{12}C_{\text{g.s.}} + e^{+} + \nu_{e} \]

\[ \beta \text{ decay of } ^{12}N_{\text{g.s.}}: \]

\[ \tau = 15.9 \text{ ms} \]

\[ \text{max KE of } e^{+} = 16.3 \text{ MeV} \]

• \( \sigma \) well-known (~5%) but increasingly small (4% of \( \sigma_{\text{QE}} \) at 250 MeV, 0.5% at 400 MeV)

• signature: low E \( \mu^{-} \) followed by delayed \( e^{+} \) from \( \beta \) decay of \( ^{12}N_{\text{g.s.}} \)
Deuterium

• neutrino QE scattering on D$_2$ ($Q^2 \rightarrow 0$)
  (re: G. Garvey and R. VandeWater, explored for LBNE near detector)

\[ \nu \mu \ d \rightarrow \mu^- \ p \ p_s \]

\[ \frac{d\sigma}{dQ^2} |_{Q^2 = 0} = \frac{G^2 \cos^2 \theta}{2\pi} \left[ F_1^2(0) + G_s^2(0) \right] \]
\[ = \frac{G^2 \cos^2 \theta}{2\pi} \left[ 1 + 1.267 \right] = 2.08 \times 10^{-38} \text{cm}^2 \text{GeV}^{-2} \]  (less than 1% uncertainty)

(first mention of this in ANL paper, 1977)

• at $Q^2=0$, the cross section is determined by neutron $\beta$ decay;
  use a light target to minimize nuclear effects
  - event topology: see a $\mu +$ very little vertex activity

• idea is that could use low $Q^2$ events at different E's and positions
  to measure energy and radial dependence of flux
Conclusions

• $\sigma_{\nu}$’s in the E range relevant to present & future $\nu$ oscillation exps ($\sim 0.1$-$10$ GeV) are not nearly as well known as their low and high energy counterparts
  - *multiple processes that contribute in this transition region & associated nuclear physics make this region complicated*

• modern data is turning up some surprises
  - *$\nu$-nucleus QE scattering is not a standard candle!*

• there are a few interactions with well-known cross sections at these E’s
  - ($\nu$+e$^-$ scattering, DIS, $\nu$-$D_2$ scattering as $Q^2 \rightarrow 0$, and $^{12}C \rightarrow ^{12}N_{g.s.}$)

• beyond that, we need better $\sigma_{\nu}$ determinations from experiments with solid flux predictions
  - (ArgoNeuT, $\mu$B, MINER$\nu$A, MB, NOMAD, NO$\nu$A, SB, T2K ... $\nu$STORM)
Additional Reading

* Rev. Mod. Phys. 84, 1307 (2012)
  review of all neutrino cross sections
  [http://rmp.aps.org/abstract/RMP/v84/i3/p1307_1](http://rmp.aps.org/abstract/RMP/v84/i3/p1307_1)

  discussion of quasi-elastic scattering
Backups
In Two Dimensions

- data/MC disagreement in MiniBooNE $\nu_\mu$ QE sample follows lines of constant $Q^2$ not $E_{\nu}$ … cross section not a flux problem

$M_A = 1.0$ GeV in RFG:

after increase $M_A$:

(both relatively normalized)
We now calculate the antineutrino spectrum by scaling this experimentally deduced neutrino spectrum with the ratio of antineutrino to neutrino spectrum as obtained from a Monte Carlo. This ratio is not sensitive to the spectral shape introduced into the Monte Carlo. We find that the antineutrino flux, integrated over energy, is $2.4 \times 10^5$ antineutrinos/cm$^2$ pulse for $5 \times 10^{15}$ protons on target per pulse ($5 \times 10^{12}$ protons/pulse is a typical proton flux in our experiment); the antineutrino flux-energy (product of antineutrino flux and antineutrino energy) is $3.4 \times 10^5$ antineutrinos GeV/cm$^2$ pulse. The errors in these calculations are estimated to be $\sim 12\%$. These errors include uncertainties due to assumptions in the Monte Carlo program and statistical errors in the experimentally determined neutrino flux. We estimate that approximately 10% of the charged-current interactions in this experiment come from neutrino contamination.