Neutrino-Nucleus Interactions

J. Carlson - LANL

• Different energy and momentum regimes and different processes (beta decay, ...)
• `Realistic` model ingredients
• A=2 (deuteron)
• Light Nuclei (A ≈ 12)
• Medium/Heavy Nuclei (Ar, Pb, ...)
• Relations to matter
• Outlook

see Formaggio and Zeller, RMP, 2013
Scholberg, ARNPS, 2012
Accelerator Neutrinos

SuperK

MINOS

MINERva

MicroBooNE
This paper presents a review on the field of inclusive quasielastic electron-nucleus scattering. It discusses the approach used to measure the data and includes a compilation of data available in numerical form. The theoretical approaches used to interpret the data are presented. A number of results obtained from the comparison between experiment and calculation are then reviewed. The analogies to, and differences from, other fields of physics exploiting quasielastic scattering from composite systems are pointed out.

CONTENTS

I. Introduction 189
II. Electron-Nucleus Scattering in the Impulse Approximation 191
A. Electron-nucleus cross section 191
B. Electron scattering off a bound nucleon 193
C. The nuclear spectral function 193
D. Contribution of inelastic processes 195
E. Different implementations of the IA scheme 196
III. Final-State Interactions 197
IV. Experiments 201
V. Data 203
VI. Extraction and Use of Nucleon Form Factors 203
VII. Scaling 206
VIII. Light Nuclei 210
IX. Euclidean Response 212
X. $L/T$ Separation And Coulomb Sum Rule 214
XI. Coulomb Corrections 216
XII. Nuclear Matter 218
XIII. Related Areas 219
XIV. Conclusions 221
Acknowledgments 221
References 222

I. INTRODUCTION

The energy spectrum of high-energy leptons, electrons in particular, scattered from a nuclear target displays a number of features. At low energy loss, peaks due to elastic scattering and inelastic excitation of discrete nuclear states appear; a measurement of the corresponding form factors as a function of momentum transfer gives access to the Fourier transform of nuclear transition densities. At larger energy loss, a broad peak due to quasielastic electron-nucleon scattering appears; this peak—very wide due to nuclear Fermi motion—corresponds to processes by which the electron scatters from an individual, moving nucleon, which, after interaction with other nucleons, is ejected from the target. At even larger energy loss, peaks that correspond to excitation of the nucleon to distinct resonances are visible. At very large energy loss, a structureless continuum due to deep inelastic scattering on quarks bound in nucleons appears. A schematic spectrum is shown in Fig. 1. At momentum transfers above approximately 500 MeV/c, the dominant feature of the spectrum is the quasielastic peak.
Inclusive electron scattering at larger $q$

measure electron kinematics only

\[
\frac{d^2\sigma}{d\Omega_e dE_{e'}} = \left( \frac{d\sigma}{d\Omega_{e'}} \right)_{M} \left[ \frac{Q^4}{|q|^4} R_L(|q|, \omega) \right. \\
\left. + \left( \frac{1}{2} \frac{Q^2}{|q|^2} + \tan^2 \frac{\theta}{2} \right) R_T(|q|, \omega) \right]
\]
Simplest models fail at 30-40% level (too small)
requires two-nucleon currents and correlations
Nuclear Interactions and Currents

Non-relativistic nucleons w/ 2, 3-body interactions, currents

\[ H = \frac{1}{2m} \sum_i p_i^2 + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} \]

\[ J = \sum_i \mathbf{j}_{1;i} + \sum_{i<j} \mathbf{j}_{2;ij} + \ldots \]

Deuteron Potential Models with Different Spin Orientations

Forrest, et al, PRC 1996

t20 experiment Jlab R. Holt
Many measurements in EM sector

Currents and elastic/transition form factors

$^{12}$C elastic form factor

Hoyle state transition form factor

2 Nucleon charge operators (relativistic corrections) are small
2-Nucleon Currents

Form Factors

<table>
<thead>
<tr>
<th>$F_C(Q)$</th>
<th>$F_M(Q)$</th>
</tr>
</thead>
</table>

$^3$He

Magnetic Moments

EM Transitions

Wiringa, Pastore, Schiavilla, et al
**Path Integral Algorithms:** \[ \Psi_0 = \exp \left[ -H \tau \right] \Psi_T \]

Explicit Final States \[ \sigma \propto |\langle f | J(q) | i \rangle|^2 \]

Sum Rules: ground-state observable \[ S(q) = \int d\omega \ R(q, \omega) = \langle 0 | O^\dagger(q) \ O(q) | 0 \rangle \]

Imaginary Time Correlations (Euclidean Response) \[ \tilde{R}(q, \tau) = \langle 0 | \ j^\dagger \ \exp[-(H - E_0 - q^2/(2m))\tau] \ j | 0 \rangle \]
Quasi-elastic electron scattering on $^{12}$C

Enhancement in Transverse channel
Explicit 0+, 2+, 4+ states important at q=300 MeV/c
**Neutral Current Sum Rules in $^{12}$C**

**Sum Rules**

cross-section depends upon 5 response fns

all except longitudinal response enhanced including axial-vector interference

sum rules - ground state expectation value enhanced even at very low $q$, but strength inaccessible to low energy neutrinos
Shell Model Calculations of Beta Decay typically require a quenching (reduction) of $g_A$ by $\sim 0.75$

**Rate reduction by 30-40%**

Martinez-Pinedo and Poves, PRC 1996

<table>
<thead>
<tr>
<th>A</th>
<th>Simple</th>
<th>I-Body current</th>
<th>I+2 current</th>
<th>Exp$^\ominus$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A=3$</td>
<td>2.45</td>
<td>2.27</td>
<td>2.28$^*$</td>
<td>2.28</td>
</tr>
<tr>
<td>$A=6$</td>
<td>2.4</td>
<td>2.15</td>
<td>2.19</td>
<td>2.2</td>
</tr>
<tr>
<td>$A=7$</td>
<td>2.58</td>
<td>2.29</td>
<td>2.39</td>
<td>2.4</td>
</tr>
<tr>
<td>$A=10$</td>
<td>2.45</td>
<td>2.06</td>
<td></td>
<td>2.34</td>
</tr>
</tbody>
</table>

Smaller ($\sim 10\%$) quenching reproduced in light nuclei

( preliminary)
Astrophysical Energy Neutrinos

- Energies up to 50 - 100 MeV
- Explicit final states and inclusive scattering measurable
- Nucleon couplings pretty well known
- What are the roles of nuclear structure, two nucleon correlations and currents?
- Momentum transfer much less than QE, but greater than beta decay.
Neutrino-Deuteron Scattering

A=2

currents fit to tritium beta decay
small effects from 2-nucleon currents
small (few %) model dependence

typically ~20% accuracy from reactor experiments

Shen, et al., PRC 2012

Formaggio and Zeller
Neutrino-⁴He Scattering

<table>
<thead>
<tr>
<th>$T$ [MeV]</th>
<th>$(\nu_e, \bar{\nu}_e)$</th>
<th>$(\bar{\nu}_e, \bar{\nu}_e')$</th>
<th>$(\nu_e, e^-)$</th>
<th>$(\bar{\nu}_e, e^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$1.47 \times 10^{-6}$</td>
<td>$1.36 \times 10^{-6}$</td>
<td>$7.40 \times 10^{-6}$</td>
<td>$5.98 \times 10^{-6}$</td>
</tr>
<tr>
<td>4</td>
<td>$1.73 \times 10^{-3}$</td>
<td>$1.59 \times 10^{-3}$</td>
<td>$8.60 \times 10^{-3}$</td>
<td>$6.84 \times 10^{-3}$</td>
</tr>
<tr>
<td>6</td>
<td>$3.34 \times 10^{-2}$</td>
<td>$3.07 \times 10^{-2}$</td>
<td>$1.63 \times 10^{-1}$</td>
<td>$1.30 \times 10^{-1}$</td>
</tr>
<tr>
<td>8</td>
<td>$2.00 \times 10^{-1}$</td>
<td>$1.84 \times 10^{-1}$</td>
<td>$9.61 \times 10^{-1}$</td>
<td>$7.68 \times 10^{-1}$</td>
</tr>
<tr>
<td>10</td>
<td>$7.09 \times 10^{-1}$</td>
<td>$6.54 \times 10^{-1}$</td>
<td>$3.36$</td>
<td>$2.71$</td>
</tr>
</tbody>
</table>

Thermal averaged cross sections
Few % impact of two-nucleon currents
Fairly simple nuclei;
no bound excited states
Achievable errors $\ll 10\%$

convergence in each partial wave

Gazit, Barnea, PRL 2007

No data to compare with
Neutrino-\textsuperscript{12}C Scattering

Experiment: Karmen and LSND

\textbf{\( \sigma(\nu_e, e^- \rightarrow \text{^{12}C}_{\text{g.s.}}) \)} \((10^{-42}\text{ cm}^2)\)

\begin{itemize}
  \item KARMEN, PPNP 32, 351 (1994)
  \item LSND PRC 64, 065001 (2001)
  \item Fukugita, et al.
\end{itemize}

\( \nu_e \) charged current to \textsuperscript{12}N
from muon decay at rest

theory errors estimated at \( \sim 20\% \), Fukugita et al., 1988
**Neutrino-$^{12}$C Scattering**

Neutrino charge current scattering from $^{12}$C (LSND/Karmen)

| $^{12}$C($\nu_e$, $e^-$)$^{12}$N$_{g.s.}$ | Stopped $\pi/\mu$ | KARMEN | 9.1 ± 0.5(stat) ± 0.8(sys) | 9.4 [Multipole](Donnelly and Peccei, 1979) 9.2 [EPT](Fukugita et al., 1988). 8.9 [CRPA](Kolbe et al., 1999b) |
| $^{12}$C($\nu_e$, $e^-$)$^{12}$N$_{g.s.}$ | Stopped $\pi/\mu$ | E225 | 10.5 ± 1.0(stat) ± 1.0(sys) | |
| $^{12}$C($\nu_e$, $e^-$)$^{12}$N$_{g.s.}$ | Stopped $\pi/\mu$ | LSND | 8.9 ± 0.3(stat) ± 0.9(sys) | |

| $^{12}$C($\nu_e$, $e^-$)$^{12}$N$_{g.s.}$ | Stopped $\pi/\mu$ | KARMEN | 5.1 ± 0.6(stat) ± 0.5(sys) | 5.4-5.6 [CRPA](Kolbe et al., 1999b) 4.1 [Shell](Hayes and S, 2000) |
| $^{12}$C($\nu_e$, $e^-$)$^{12}$N$_{g.s.}$ | Stopped $\pi/\mu$ | E225 | 3.6 ± 2.0(tot) | |
| $^{12}$C($\nu_e$, $e^-$)$^{12}$N$_{g.s.}$ | Stopped $\pi/\mu$ | LSND | 4.3 ± 0.4(stat) ± 0.6(sys) | |

| $^{12}$C($\nu_\mu$, $\mu^-$)$^{12}$N$_{g.s.}$ | Decay in Flight | LSND | 56 ± 8(stat) ± 10(sys) | 68-73 [CRPA](Kolbe et al., 1999b) 56 [Shell](Hayes and S, 2000) |

Little evidence for important 2N current effects for 30-100 MeV neutrinos
Neutrino - Ar Scattering

inclusion $u_e$ charged current $^{40}$Ar

Athar, et al, 2004

anti-$\nu$ charged current to Cl

Significant differences
Neutrinos in Matter

• Many studies in mean-field models, perhaps accurate enough in many cases

• Virial expansion should be accurate in hot dilute matter

• Should use same interactions/currents in nuclei and matter. More reliable constraints.

• Matter results are less directly connected to experiment for astrophysical energies, particularly for very neutron-rich matter.

Can we identify important regimes where more accuracy is required; similarities in nuclear and matter responses?
Status and Outlook

- Microscopic inputs reasonably well defined (interactions, currents)
- Future inputs on one- and two-nucleon level from lattice QCD
- Accurate calculations possible in light nuclei
- Critical for accelerator neutrino energies
- What future experiments on nuclei are most valuable?
- More realistic studies of neutrinos in matter (Reddy, Schwenk, …)