### *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*





# MINOS





# SuperK MINERva MicroBooNE

MINERva



### Accelerator Flectron/Neutrino Scatter peak. *Accelerator Electron/Neutrino Scattering*



Benhar, Day, Sick, RMP 2008

### **example 3 +** *A* **+** The right-hand side of  $\mathbb{R}^n$  can be rewritten sin-Inclusive electron scattering at larger q

in which an electron of inclusion  $\mathcal{L}$  and  $\mathcal{L}$  in the initial four-momentum  $\mathcal{L}$ duced by longitudinally !*L*" and transversely !*T*" polarmeasure electron kinematics only



## *Simple Models of QuasiElastic Neutrino Scattering*



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

$$
H = \frac{1}{2m} \sum_{i} p_i^2 + \sum_{i < j} V_{ij} + \sum_{i < j < k} V_{ijk}
$$
\n
$$
\mathbf{J} = \sum_{i} \mathbf{j}_{1;i} + \sum_{i < j} \mathbf{j}_{2;ij} + \dots
$$



Deuteron Potential Models with Different Spin Orientations



### t20 experiment Jlab R. Holt



Forrest, et al, PRC 1996

#### *M*1*/q* on a grid of small *q* values. Consequently, the lon- $\frac{1}{2}$ elastic (bottom left), and transverse elastic (upper right), and transverse elastic (upper right), and the contract of  $\frac{1}{2}$ in the last of the introduced with the introduced with  $\mathcal{H}$  in the introduced with  $\mathcal{H}$  and  $\mathcal{H}$ approximation (IA), and with the addition  $\mathcal{A}$  , and with the addition of MEC contri- $\mathbf{b}$ utions. The results are compared to the experimental data of  $\mathbf{b}$ indicated in the legend. -100 -90 -80 E( τ) (MeV)  $O^4$ Sd  $^{12}C$ 0.02 0.04  $\circ$  ${}^{12}C(0^+)$ GFMCGIFAV18HS *Many measurements in EM sector Currents and elastic/transition form factors*

 $p$ 



mial fit (in powers of *q*<sup>2</sup>) to the calculated *C*2*/q*<sup>2</sup> and

 $\overline{\phantom{a}}$ z inucleon charge operators are compared to the experimental data. The second of the state of the state of 12C is the famous model of the famous model is the famous model in the famous mode 2 Nucleon charge operators It is interesting that it is a particular model in the state for shell model in the state for shell model calculations of the state for shell model in the state for state for state for state for state for shell model calcu tions are the corrections, external the small (relativistic corrections)



### Hoyle state transition form factor







### Magnetic Moments

EM **Transitions** 

![](_page_7_Picture_3.jpeg)

# **Path Integral Algorithms:**  $\Psi_0 = \exp[-H\tau] \Psi_T$ Explicit Final States  $\sigma \propto |\langle f| \mathbf{J}(\mathbf{q})| i \rangle|^2$

### Sum Rules: ground-state observable  $S(q) =$  $d\omega$   $R(q,\omega) = \langle 0|O^{\dagger}(q) O(q)|0\rangle$

Imaginary Time Correlations(Euclidean Response)  $\tilde{R}(q,\tau) = \langle 0 | \mathbf{j}^{\dagger} \exp[-(\mathbf{H} - \mathbf{E_0} - \mathbf{q^2}/(2\mathbf{m}))\tau] \mathbf{j} |0\rangle >$ 

![](_page_8_Figure_3.jpeg)

#### strangulation in *R*<sub>I</sub> (*q*, *q*) *d* labeled GFMC-*O*1*<sup>b</sup>* and GFMC-*O*1*b*+2*b*), thus o↵setting the quenching noted in (ii) in the quasi-elastic peak. of the fundamental parameters of  $\mathbf{r}$ be measured at the Deep United States and Deep United States and Neutrino Experiment At 2012. Quasi-elastic electron scattering on <sup>12</sup>C

![](_page_9_Figure_1.jpeg)

netic transverse functions. Because pion productions. Because pioneers and productions. Because pioneers and p Lovato, et al, PRL 2016  $\frac{1}{\sqrt{2}}$  $\overline{\phantom{a}}$ 

 $\overline{A}$  result of this study, a consistent picture of this study, a consistent picture of the theorem -xnlicit ()+  $/$ + 4+ states, Explicit 0+, 2+, 4+ states important at q=300 MeV/c particular the *q* = 570 MeV/c case. We conclude by updating in Fig. 3 the results for the Enhancement in Transverse channel

![](_page_10_Figure_0.jpeg)

![](_page_10_Figure_1.jpeg)

FIG. 2. (Color online) The response functions *R*↵ in the all except longitudinal response enhanced  $t$ ained with one-body only (dashed lines) and one- and twobody (solid lines) terms in the NC. The inset shows the tails including axial-vector interference

 $\mathbf{b}$  terms in the NC are indicated by the dashed (solid) terms in the dashed (solid) terms in the dashed (solid) sum rules - ground state expectation value we find that Set II leads to very similar results. Note that Set II leads to very similar results. Note that S

factor *C*↵, which makes *S*1b ↵(*q*) ! 1 in the large *q* limit. enhanced even at very low than *S*1b ↵ for ↵ 6= 00*,* 0*z*. In a simple ↵-cluster pic-**Lure of 12C** inaccessible to low energ ↵(<sup>4</sup>He)*/C*↵(<sup>4</sup>He), as is indeed verified in the acenhanced even at very low q, but strength inaccessible to low energy neutrinos

### *Low Momentum Transfer: GT Beta Decay*

![](_page_11_Figure_1.jpeg)

### *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.

![](_page_13_Figure_0.jpeg)

Nakamura, et al, 2001 hen, et al., PRC 2012

ring

typically  $\sim$  20% accuracy from reactor experiments

Formaggio and Zeller

![](_page_13_Picture_849.jpeg)

![](_page_13_Picture_850.jpeg)

### *Neutrino-4He Scattering*

![](_page_14_Picture_860.jpeg)

lV erage d cross sections v % impact of two-nucleon c Thermal averaged cross sect Thermal averaged cross sections V TO IMPACE OF EWO HOCICOH C Few % impact of two-nucleon currents

 $\overline{\phantom{a}}$   $\overline{\phantom{a}}$   $\overline{\phantom{a}}$   $\overline{\phantom{a}}$ *J*#1  $$ no bound excited states is the angular momentum of the 4He, and *Zf* is the charge chievable errors  $\leq$  10% Because of the sample nuclei: Fairly simple nuclei; no bound excited states  $\Delta$  is small. Although presented for  $\Delta$ Achievable errors  $\ll$  10 Achievable errors « 10%

![](_page_14_Figure_4.jpeg)

convergence in each partial wave Epistem, Colliver Serice, 111 d

Gazit, Barnea, PRL 2007 Gazil, Dallica, ITTL ZUUT [5] T. Yoshida *et al.*, Phys. Rev. Lett. **96**, 091101 (2006).  $\frac{1}{\sqrt{6}}$  N. Ohnishi, K. K. K. S. Yamada, astro-philipse structure s

No data to combare with ne case so compare when Haxton, Astrophys. J. **356**, 272 (1990).  $\blacksquare$  B. No. data t **No data to compare with** 

### **Meutrino-<sup>12</sup>C Scattering**

# Experiment: Karmen and LSND

![](_page_15_Figure_2.jpeg)

υ<sub>e</sub> charged current to <sup>12</sup>N exclusive reaction <sup>12</sup>C(⌫*e, e*) <sup>12</sup>N from *µ* decay-at-rest neutront mouth deedy actest from muon decay at rest

 $A = \frac{1}{2}$ theory errors estimated at ~ 20 %, Fukugita et al., 1988

#### **TABLE VII Example Video Measured (flux-averaged) cross-section Measured (flux-averaged) cross-sections on various nuclei at low energies (fluxe-averaged) cross-sections on various nuclei at low energies (1-300 MeV). Exper** tal data gathered from the LAMPF (Willis *et al., 1980)*, Karoline *et al.*, 1998; Bodimann *et al.*, 1991; Maschuw, 1998; Ruf, 2005; Zeitnitz *et al.*, 1994), E225 (Krakauer *et al.*, 1992), LSND (Athanassopoulos *et al.*, 1997; Auerbach *et al.*, 2002,  $\blacksquare$  $\blacksquare$

#### Neutrino charge current scattering emission at *E*⌫ = 811 keV. Selected comparisons to theoretical predictions, using di↵erent approaches are also listed. The from 12C (LSND/Karmen) theoretical predictions are not meant to be exhaustive.  $\sum_{i=1}^n \frac{1}{i}$ Stopped ⇡*/µ* LSND 8*.*9 *±* 0*.*3(stat) *±* 0*.*9(sys) 8.9 [CRPA] (Kolbe *et al.*, 1999b)  $f_{120,300}$  20 (LCNID 1V 21200 01) Stopped ⇡*/µ* E225 3*.*6 *±* 2*.*0(tot) 4.1 [Shell] (Hayes and S, 2000)

![](_page_16_Picture_745.jpeg)

### Little evidence for important 2N current effects for 30-100 MeV neutrinos <sup>12</sup>Ng*.*s*.* Decay in Flight LSND <sup>56</sup> *<sup>±</sup>* 8(stat) *<sup>±</sup>* 10(sys) 68-73 [CRPA] (Kolbe *et al.*, 1999b) constitute and interest in experiment channel used in the second in experiment of the second in the second in experiment of the second in the second in

### **Neutrino - Ar Scattering** decay strength corresponding to ground state transicorresponding to this transition is taken. This taken is taken to the transition is taken. This being the transition is taken.

![](_page_17_Figure_1.jpeg)

Fig. 3. Total cross section <sup>σ</sup> vs. *<sup>E</sup>* for <sup>ν</sup>*<sup>e</sup>* <sup>+</sup>40Ar <sup>→</sup> *<sup>e</sup>*<sup>−</sup> <sup>+</sup>40K<sup>∗</sup> nclusive  $\Pi$ , charged current  $^{40}$ inclusive  $\upsilon_{\text{e}}$  charged current <sup>40</sup>Ar Athar, et al, 2004

 $\mathbf{f}$  with Fermi function  $\mathbf{f}$  and  $\mathbf{f}$  a anti-ν charged current to Cl sults of Bueno et al. [13] (dashed-dotted line).

Expected event rates for a 3 kT argon detector for a supernova occurring at 10 kpc corresponding to ⟨*E*ν*<sup>e</sup>* ⟩ = 11 MeV, ⟨*E*ν¯*<sup>e</sup>* ⟩ = 16 MeV and Significant differences

### *Neutrinos in Matter*

- Many studies in mean-field models, perhaps accurate enough in many cases
- Virial expansion should be accurate inhot 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, ...)

![](_page_19_Figure_7.jpeg)