Inclusive Electron- and Neutrino-Nucleus Scattering: Correlations and Currents

- Motivation
- •Interactions and currents
- Review of electron scattering
	- •Sum rules
	- •Euclidean Response
- •Electron/Neutrino Scattering from the Deuteron
- Sum Rules for A=12
- •Near Future

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Response Functions probes of structure and dynamics parent value of n, as given by (2), and to correct \sqrt{r} \mathbb{R}^n **Kes** ponse Functions; nes of st Figure 3 shows a comparison of our new values EXCITATIONS IN LIQUID He $\frac{1}{2}$ ucture and dynamics

tracting the condensate component from n(p). The

Extraction of condensate $H(x)$ and $H(x)$ and $H(x)$ Extraction of condensate fraction in liquid He almost the same as (5) \mathcal{F} in inquirement is equal to \mathcal{F}

FIG. 6. The energy spectrum of excitations. Curve A is the spectrum $E_2(k)$ computed from Eq. (61). Curve B is the spectrum $E_1(k)$ computed with the simpler wave function (5) . Curve C is the ွှ Landau-type spectrum used by de-**NERGY** Klerk et al.⁴ to fit the second sound and specific heat data. Curve Dis a Landautype spectrum with p_0 taken the same as
in A, and μ and Δ chosen to fit the specific heat data. For small k , all curves are asymptotic to the line
 $E = \hbar c k$.

phonon-roton $T_{\rm eff}$ approximation (59), which gives $T_{\rm eff}$ error (b), ought to be about as the spectrum in liquid as \mathcal{P} code channels by approximations are based as \mathcal{P} | spectrum in liquid He

Sears, et al, PRL, 1982 $S(Q)$ and , and the product $O(Q)$ and \mathbf{t} , we regard the value of \mathbf{t} we regard the snumber as a as a set of \mathbf{t} afr) tor Simple Lig Considerable painting were the nu- 882 S(Q) and g(r) for Simple Liquids

 ϵ ϵ (Ref. 8). The 1994 Nobel Prize – Shull & Brockhouse more examples: Cold Atomic Gases, ... From Pure Pure High Tc

 \mathbb{R}^n . This singular behavior enhances the approximation is the approximation of \mathbb{R}^n .

how na \mathbb{R}^n

 $t_{\rm s}$

plains why n(p) for 2.12 K already exhibits an increase at small p which is about half the total in-

 \mathbb{R}^n \mathbf{r}

 $T_{\rm eff}$ and 2.12 K are listed in Table I. In Ref. 13 it was, \mathbb{R}^n is indeed important at all temperatures while y

and bp ' terms in (5) are of impor-

Fig. 5.2 The pair-distribution function $g(r)$ obtained from the experimental

(e, e') Inclusive Response: Scaling Analysis Donnelly and Sick (1999) ${}^{3}\text{He}$ ${}^{4}\text{He}$ $+$ q=300 $+ q=300$ $1.00 \,$ \sim q=400 \times q=400 0.8 \diamond q=500 \circ q=500 \div q=600 \div q=600 0.75 \overline{p} q=700 $- x q = 700$ 0.6 $f_{L,T}(\psi')$ 0.50 0.4 0.25 0.2 0.00 0.0 Ω -2 -2 Ω $\eta l'$ $\eta l'$

Single nucleon couplings factored out
M Large enhancement of transverse over longitudinal response Momenta of order inverse internucleon spacing:

Requires beyong single nucleon physics **Requires beyond single nucleon physics**

Longitudinal/Transverse separation in ¹²C

duce large effects in combination with ground-state

wave functions calculated *including* the short-range *n*-*p*

correlations. As most previous calculations were based

on independent-particle-type wave functions, the small-

ness of the resulting MEC contributions is thus under-

stood. To verify this point further, Carlson *et al.* have

repeated their calculation using the same operators, but

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Euclidean response, despite inherent drawbacks, is a

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From the above discussion it becomes clear that the

mentum transfer. It decreases toward the larger *Q*²

The results of Carlson *et al.* also show, somewhat sur-

Nuclear Interactions:

AV18 : excellent fit of NN data pion exchange plus phenomenology TNI: Two-pion exchange plus three-pion-exchange plus phenomenological short-range repulsion

Chiral Interactions: LO, NLO, N2LO, N3LO increasing order results in better fits to data uncertainty estimates

 Consistency of two plus three nucleon interactions New local interactions at LO..N2LO

^N²LO bands are obtained by varying ^R⁰ between 0.⁸ [−] ¹.2 fm (with a spectral-function cutoff ^Λ! = 800 MeV).

Gezerlis, et al., PRL 2013

 \overline{a}

QMC methods

Basic Idea: project specific low-lying states from initial guess (or source)

$$
\Psi_0 = \exp \left[-H\tau \right] \Psi_T
$$

Use Feynman path integrals to compute propagator $\exp[-H\tau] = \prod \exp[-H\delta\tau]$ Applications: condensed matter (Helium, electronic systems, ... nuclear physics (light nuclei, neutron matter, SMMC...) atomic physics (cold atoms,...) Various formulations: DMC/GFMC, AFMC, AFDMC, Lattice $\exp[-H\delta\tau] \approx \exp[-T\delta\tau] \exp[-V\delta\tau]$ diffusion branching

-MC Algorithm: *GFMC Algorithm:*

ADVANCING FROM THE IBM BG/P TO THE BG/Q • ADLB under UNEDF resulted in code working well on BG/P: \Box 2 Gbytes and 4 cores (each one thread) per hoce B ranching random, walk in 34 $(36$ for 12 C) dimensions Asynchronous Dynamic Load Balancing (ADLB) Library Each step 4 and very neglige the working went on Burr.

- G by f **e**s so OpenMP used for the 4 cores (th 12 C(0⁺) needs 2 Gbytes so OpenMP used for the 4 cores (threads) *A*
- *•* 48 racks of nodes *•* 19.6 Pbytes (22⇥10¹⁵) disk $-$ C(0) heghs 2 Gbydrs so OpenNr used for *z* $\frac{1}{2}$ complement and the transmitted of the context (2 GB for ¹²C gs)
- offers new noskitkilike and otters hew possibilities and cha 62 · BG/Q offers new posignifics and than east algebra for each step
	- *<u>fo cores</u>* each 4th by us, three cay prive 4404 m₁ *•* 80 matrix CS st. – 16 Gbytes, through the state of threads) per noded math/CS staff at ANL
	- -48×1024 nodes

• 12.8 GFLOP/core: 205 GFLOP per node, branats/noderamdateach/arts2vorthd4ntmansale use^{Other 12} C states need much more memory/rank (Talttice calculations) Sim flaro branadsinogeram danaa walks with dimeans algebra

- 1/3 of Mira one row (16 racks) of Mira one row (16 racks) of the miral extension of the miral extension of *•* Early Science grant gave access to machine as it was still being installed – One must be patient!
- **Convert** $-$ ADLB performance Δ with better on BG/Q with no modifications!

up to ~2M threads

– OpenMP scales well to more threads

Other methods: NCSM, Coupled Cluster, ...

Spectra of Light Nuclei

Spectra must be correct to describe low-energy transitions, reactions, etc.

¹²C Electromagnetic Charge Form Factor

Results - Longitudinal form factor

Ground State - Hoyle State Transition form factor

• Data from M. Chernykh *et al.*, Phys. Rev. Lett. 105, 022501 (2010)

²) *ftr* FORM FACTOR

include irreducible contributions only.

nucleon potential has been derived in Ref. [7] up to

the possible time orderings is shown for the 1 assort 5, 5ema Pastore S, Schiavilla R, Goity J L. Phys. Rev. C, 2008, 78: irreducible diagrams and recoil-corrected recoil-corrected recoil-corrected reducible α \mathcal{H} and the isoscalar function of \mathcal{H} and the isoscalar function of \mathcal{H} dstore t , behiaving it, Golty J L. I hys. Hev. C , 2006, 18.
 ϵ 4009

An important aspect of the derivation of the EM

nucleon kinetic energy differences to pion energies

standard convection and spin-magnetization nucleon

46% (18%) of the total calculated nd (n³He) value.

study, Λ varies from 500 meV which corresponds from 500 meV which corresponds to 700 meV which corresponds to
The corresponding to 700 meV which corresponds to 700 meV which corresponds to 700 meV which corresponds to 70

Pastore S, Girlanda L, Schiavilla R, Viviani M, Wiringa R B. Phys. Rev. C, 2009, 80: 034004

np] at thermal neutron energies.

Ray L, van Kolck U. Phys. Rev. C, 1996, 53: 2086, 53: 2086, 53: 2086, 53: 2086, 53: 2086, 53: 2086, 53: 2086,
Rev. C, 1996, 53: 2086, 53: 2086, 53: 2086, 53: 2086, 53: 2086, 53: 2086, 53: 2086, 53: 2086, 53: 2086, 53: 20

 n p capture, μ_v(A=3): isovector $\mu(D)$, $\mu_s(A=3)$: isoscalar

can than the AV18. From the AV18. From this perspective, the AV18. From this perspective, the AV18. From this

of the unitary transformations. However, they are the unitary transformation of the unitary methods. However, they are they are they are they are they are the unitary methods. However, they are the unitary methods. However α is that derived by Park in Ref. in all ideal, E. E. in all deck, S. in astorce, β . astorce, α . Werkelman R, Schiavilla, and M. Viviani, Phys. Rev. C 87, 014006 in covariant perturbation theory, since the since theory, since the since theory, (2013) . (2013) (20.5) M. Piarulli, L. Girlanda, L. E. Marcucci, S. Pastore,
B. Sekin ille and M.) (ividei: Phys. Bay G. 87, 81,4996 R. Schiavilla, and M. Viviani, Phys. Rev. C 87, 014006
(2013). $\frac{1}{2}$ He respectively—and the circular position $\frac{1}{2}$

17 Carlson J, Schiavilla R. Rev. Mod. Phys. 1998, 70: 743

A ≤ 10 Magnetic Moments with Chiral EFT currents Hybrid calculations using AV18+IL7 wave functions and \mathcal{L}^{F} exchange currents developed in: \mathcal{L}^{F} Pastore, Schiavilla, & Goity, PRC **78**, 064002 (2008) ; Pastore, *et al.*, PRC **80**, 034004 (2009)

a se 10 magnetic momentum constituit de la constitución de la constitución de la constitución de la constitució
A segunda

Pastore, et al, Phys. Rev. C 87, 035503 (2013) ; arXiv:1302.5091

$A \leq 9$ M1 TRANSITIONS W/ χEFT EXCHANGE CURRENTS

- dominant contribution is from OPE
- five LECs at N3LO
- d_2^V and d_1^V are fixed assuming Δ reso- $\ddot{\mathsf{t}}$ ² and d^V nance saturation
- d^S and c^S are fit to experimental μ_c and $\mu_S(^3\text{H}/^3\text{He})$
- c^V is fit to experimental $\mu_V(^3\text{H}/^3\text{He})$
- $\Lambda = 600 \text{ MeV}$

Pastore, Pieper, Schiavilla & Wiringa

PRC **87**, 035503 (2013)

Two-nucleon currents critical to understand low-energy transitions

Higher resolution: Momentum Distributions

come more tightly bound, the fraction of nucleons at zero

10 Be are shown in Fig. 8. Also shown in

ρn(k) − ρp(k); this difference is very much like the two much like the two much like the two much like the two
Difference is very much like the two much like the two much like the two much like two much like two much lik halo neutrons in ⁶He shown in Fig. 4, again with a dip

at zero momentum, appropriate for the p-shell and with a dip at the usual S-wave node position, although it is

 T tables and figures of the nucleon models $\mathcal{L}_\mathcal{D}$

mentum distributions are provided online at

The tables give the proton momentum distribution, \mathcal{M} in T \mathcal{M} , in T \mathcal{M} nuclei with the understanding that neutron and proton momentum distributions are identical. For T > 0 nuclei, both proton and neutron momentum distributions are tabulated. Similarly, for J = 0 nuclei, only total nucleon momentum distributions are given, but for \mathcal{L} , the spin-down distributions for

M^J = J states are also given. In addition, the total normalization Nστ for each momentum distribution is $\mathbb{F}_{\mathbb{F}_{\mathbb{F}_{\mathbb{F}}}^{n}}$ as are the contributions to the kinetic energy. The corresponding spatial densities are provided online

at http://www.phy.anl.gov/theory/research/density/.

 \mathbf{I} in the tables, but not shown here, are distributed in the tables, are distributed in the distribution of \mathbf{I}

somewhat smeared out compared to the former case.

http://www.phy.anl.gov/theory/research/momenta/.

strength at \sim 2 fm⁻¹ due to tensor correlations High momentum components dominated by two-nucleon physics

sampled by MC integration, with one sample per pair. \blacksquare Datis to Datis pe $\frac{1}{2}$ He, $\frac{1}{2}$ and $\frac{1}{2}$ and 8/3. $\frac{1}{2}$ S' nn vs nn nn in 12 (Back-to-back pairs: pn vs pp,nn in ¹²C

momentum distributions in few-nucleon systems, which were carried out by direct MC integration over all coordi-JLAB, BNL nates, were very noisy for momenta beyond 2 fm−1, even back-to-back pairs in ¹²C

corresponding to nucleons moving back to back. The np pairs dominate α is pp pairs; they are negligible for the striking features seen in and pp

E Piasetzky *et al.* 2006 **Phys. Rev. Lett. 97** 162504. **larger than than that of phys. Rev. C 71 044615.** M Sargsian *et al.* 2005 **Phys. Rev. C 71 044615. R Schiavilla** *et al.* **2007 Phys. Rev. Lett. 98** 132501. R Subedi *et al.* 2008 **Science 320** 1475.

ues of q the ratios of np to pp momentum distributions

relative momentum q at vanishing total pair momentum Q.

slope at a characteristic value of \mathcal{H} http://www.phy.anl.gov/theory/research/momenta2/

 \mathbf{H} as a function of \mathbf{H} Neutron-Proton pairs

pair distributions with Q=0 for ³He, ⁴He, ⁶Li, and ⁸Be

 \mathbf{H} as a function of \mathbf{H} from 0 to 1.25 fm[−]¹. on the parallel computers of Argonne's Laboratory Com-

 $f_{\rm eff}$, and 4π we show pairs in 4He in Fig. 10 and for pp pairs in 4He in Fig. 10 and for pp pairs in 4He in Fig. 10 and for pn pairs in Fig. 11. The figures show a series of curves as a function of q for fixed values of Q from 0 to 1.25 fm−1, averaged over all angles between Q and q (by MC

The trends illustrated by these figures are similar to the single-nucleon momentum distributions. The pp pairs are primarily in relative ¹S⁰ states, and exhibit the \mathbb{R}^n and \mathbb{R}^n increases, this node begins to fill in, until it is largely $g_{\alpha\beta} = \frac{1}{\alpha} \int \frac{d\beta}{\beta} \, d\beta$ deuteron-like states, with the D-wave contribution filling in the S-wave node and giving the usual broad shoulder \mathbb{R}^n fm \mathbb{R}^n both pp and pn pairs decreases as Q increases, simply because there are fewer pairs with high total momenta. The numerical values for these curves may be found online at http://www.phy.anl.gov/theory/research/momenta2/,

sampling).

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pair momenta vs Q: pn vs pp,nn in ⁴He

Inclusive Scattering and Response Functions
\n
$$
R_{L,T}(q,\omega) = \sum_{f} \delta(\omega + E_0 + E_f) | \langle f | \mathcal{O}_{\mathcal{L},\mathcal{T}} | 0 \rangle |^2
$$
\nknowledge of response \circ inclusive cross-sections requires knowledge of all final states

Start with the deuteron, can enumerate all final states. Use for test of Monte Carlo codes Accurate predictions: could use to make absolute flux measurements

Electron Scattering on Deuterium

ν -Deuteron Scattering up to GeV Energy

Shen et al. (2012)

 μ -capture rates in d and ³He [Schiavilla and Wiringa (2002); Marcucci et al. (2012)]

28

Deuterons: Neutral Current Comparison of 1-body PW to isolated $p + n$ and ratio 29

FIG. 16: (color online) The "model" (P+N) NC cross sections for neutrino and antineutrino are compared with plane-wave one-body (PW 1-body) results, see text for explanation. Inset: ratio of neutrino NC versus antineutrino NC cross section.

Charged Current on Deuteron

Heavier Nuclei (A>2)

Easy to calculate Sum Rules: ground-state observable

$$
S(q) = \int d\omega \; R(q,\omega) = \langle 0|O^{\dagger}(q) \; O(q)|0\rangle
$$

Sum Rules are independent of final states (and FSI)

$$
E(q) = \int d\omega \, \omega \, R(q,\omega) = \langle 0|O^{\dagger}(q)HO(q)|0\rangle
$$

For spin-isospin independent interactions E(q) = q²/2m

For nuclear physics $E(q) > q^2/2m$, not reproduced by spectral function alone

Longitudinal and Transverse Electromagnetic Response in A=3,4, 12

(e, e') Inclusive Response: Scaling Analysis

From the above discussion it becomes clear that the

 -0.2

 0.0

 $0.2\,$

 y/m

 0.4

 0.8

 0.6

Results - Longitudinal sum rule Carbon-12 : Electron Scattering Longitudinal Sum Rule $S_L(q) = \langle 0 | \rho^{\dagger}(q) \rho(q) | 0 \rangle$

Transverse Sum Rule

Results - Transverse sum rule

•Divergent behavior at small

 $\mathcal{O}(\log n)$

contribution, most likely

experimental data made

difficult by the peak.

region, needed for a better

from the quasi-elastic

• Comparison with

experimental data.

Lovato, Gandolfi, Butler, Carlson, Lusk, Pieper, Schiavilla PRL 2013

 Two -nucleon currents contribute \sim 50% enhancement Jlab experiments, neutrino experiments

Sum Rules and Euclidean Response Real-time response

$$
R(q,\omega) = \langle 0 | \mathbf{j}^{\dagger}(q) | f \rangle \langle f | \mathbf{j}(q) | 0 \rangle \delta(w - (E_f - E_0))
$$

$$
R(q,\omega) = \int dt \langle 0 | \mathbf{j}^{\dagger}(q) \exp[iHt] \mathbf{j}(q) | 0 \rangle \exp[i\omega t]
$$

Short time 't' : sum rules Long time: higher energy resolution No general method for strongly-correlated quantum systems, typically use model final states

Short-time theories well known operator product expansion,

Cold Atoms zero-range interaction infinite scattering length Example: Unitary Fermi Gas

 4 ± 1 meaks at $d<1/m$ determined to experimental theoretical to experimental to experim $\frac{1}{\frac{0.5-1.0}{0.5-1.0-1.5-2.0-2.5}}$ peaks at q² / 2m; q² / 4m $\sum_{i=1}^{\infty}$ in particular the static structure factor, and the results are in very good agreement with $\sum_{i=1}^{\infty}$ experimental data. Functions including the unitary Fermi gas, including the unitary Fermi gas, including the u erent industrians and the transitions from the transitions of the transitions, and multi-component of the transitions, and mult with PWIA or spectral fn

program. Computing time time were made available by Los Alamos Open Supercomputing.

 $R(q,\tau) = \langle 0 | \mathbf{j}^\intercal(q) \exp[-H\tau] \mathbf{j}(q) |0 \rangle$ Imaginary-time correlator (Euclidean Response) short time : sum rules (high energy) Converts quantum dynamics to statistical mechanics long 'time' : low energy response (collective modes,...)

FIG. 30. Longitudinal "lower data set" and "lower data set and transverse representations of the set and the s
The set of the set of

 $\frac{d}{dt}$ and $\frac{d}{dt}$

wave functions calculated *including* the short-range *n*-*p*

correlations. As most previous calculations were based

 \mathcal{D}_max independent-particle-type wave functions, the small-particle-type wave functions, the small-particle-type \mathcal{D}_max

ness of the resulting MEC contributions is thus under-

stood. To verify this point further, Carlson *et al.* have

repeated their calculation using the same operators, but

with a Fermi-gas wave function. Instead of an enhance-

ment factor of 1.47 coming from MEC at !**q**!

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 $\tau =$ inverse T

Why do FSI add to high-energy response? Longitudinal electron scattering

PWIA (or spectral function): response tied to charge propagation charge propagation charged to nucleon propagation (momentum distribution) rarely appreciated

Full Interacting system: charge can propagate through pion exchange: faster response (low 'mass') adds to high-energy tail neglect of tail \mathcal{L} , and the main reason for the main reason for the \mathcal{L}

Towards (short-time) Dynamics: Euclidean Response

³He and ⁴He Transverse Euclidean Response Functions

• Excess strength in quasielastic region ($\tau > 0.01 \text{ MeV}^{-1}$)

• Larger in $A = 4$ than in $A = 3$, as already inferred from S_T

Neutrino Scattering: 2022 ative to the total method in the neutrino interior in the neutrino in the neutrino in the neutrino in the neutrino i final four-momenta are *k^µ* = (✏*,* k) and *k^µ* ⁰ = (✏⁰

$$
\left(\frac{d\sigma}{d\epsilon'd\Omega}\right)_{\nu/\overline{\nu}} = \frac{G_F^2}{2\pi^2} k'\epsilon' \cos^2 \frac{\theta}{2} \left[R_{00} + \frac{\omega^2}{q^2} R_{zz} - \frac{\omega}{q} R_{0z} + \left(\tan^2 \frac{\theta}{2} + \frac{Q^2}{2q^2} \right) R_{xx} \mp \tan \frac{\theta}{2} \sqrt{\tan^2 \frac{\theta}{2} + \frac{Q^2}{q^2}} R_{xy} \right]
$$

$$
R_{00}(q,\omega) = \sum_i \sum_f \delta(\omega + m_A - E_f) |\langle f | j^0(\mathbf{q},\omega) | i \rangle|^2,
$$

$$
R_{zz}(q,\omega) = \sum_i \sum_f \delta(\omega + m_A - E_f) |\langle f | j^z(\mathbf{q},\omega) | i \rangle|^2,
$$

$$
R_{zz}(q,\omega) = \sum_{i} \sum_{f} \delta(\omega + m_A - E_f) |\langle f | j^z(\mathbf{q}, \omega) | i \rangle|^2,
$$

\n
$$
R_{0z}(q,\omega) = \sum_{i} \sum_{f} \delta(\omega + m_A - E_f) [\langle f | j^0(\mathbf{q}, \omega) | i \rangle
$$

\n
$$
\times \langle f | j^z(\mathbf{q}, \omega) | i \rangle^* + \text{c.c.}],
$$

\n
$$
R_{xx}(q,\omega) = \sum_{i} \sum_{f} \delta(\omega + m_A - E_f) [\, |\langle f | j^x(\mathbf{q}, \omega) | i \rangle|^2
$$

\n
$$
+ |\langle f | j^y(\mathbf{q}, \omega) | i \rangle|^2],
$$

\n
$$
R_{xy}(q,\omega) = \sum_{i} \sum_{f} \delta(\omega + m_A - E_f) [\langle f | j^x(\mathbf{q}, \omega) | i \rangle
$$

\n
$$
\times \langle f | j^y(\mathbf{q}, \omega) | i \rangle^* - \text{c.c.}],
$$

functions read

*^R*00(*q,* !) = ^X

^Rzz(*q,* !) = ^X

*^R*0*z*(*q,* !) = ^X

^Rxx(*q,* !) = ^X

 $\overline{}$

h

*[|]*h*^f [|] ^j^x*(q*,* !) *[|]i*i*[|]*

2

and final scattering state of the nucleus of energies *m^A*

) scattering in quasielastic kine-

pansion of the single-nucleon four-current, in which corrections proportional to 1*/m*² (*m* is the nucleon mass)

are retained. The time component of the time component of the two-body axial component of the two-body axial c

*µ*5 *^V* in-

A realistic model for the axial weak current *j*

cludes one- and two-body terms (see Ref. [15] for a recent overview). The former follow from a non-relativistic expansion of the single-nucleon four-current, in which corrections proportional to 1*/m*² (*m* is the nucleon mass)

are retained. The time component of the two-body axial current includes the pion-exchange term whose structure and strength are determined by soft-pion theorem and current algebra arguments $\frac{2}{3}$. Its space components $\frac{2}{3}$ $\mathcal{L}=\mathcal{L}=\mathcal{L}$ $\mathcal{L}=\mathcal{L}^{\text{max}}$ transition mechanism, and axial \mathcal{L}^{max} excitation term (treated in the static limit). The values $f_{\rm eff}$ and $f_{\rm eff}$ are taken from constants are taken from constants are taken from constants are taken from $f_{\rm eff}$ the CD-Bonn one-boson-exchange potential [30]. Two \mathcal{L}^{max} sets of cuto \mathcal{L}^{max} ularize the *r*-space representation of these operators [15]:

 $E_{\rm eff}$ is the nuclear electromagnetic electromagnetic expressions for the nuclear electromagnetic electromagnetic electromagnetic electromagnetic electromagnetic electromagnetic electromagnetic electromagnetic electroma

fact the same as that adopted in our recent study of the charge form factor and longitudinal and transverse sum

are reported in Ref. [15]. The model is in

 \sim $\frac{1}{2}$

Neutrino/Anti-neutrino Scattering 5 response functions Neutral current sum rules for 12C

Present and Near Future

 \bullet Calculations of neutral and charged current scattering on the deuteron (neutrinos and anti-neutrinos) completed

^o Codes for neutral current and nearly charged current completed for use in Quantum Monte Carlo calculations

Calculations of Sum Rules (NC) completed

 \bullet Calculations for Euclidean response expected in \sim 1 year

• Studying quasi-analytic approaches to dynamic response in high q, omega region

Thanks to:

ANL devoting ~50-100M core-hours to this project plus staff/postdoc time INCITE award to NUCLEI project amount largest in country - neutrino scattering is an important goal LANL support through LDRD-DR project (PI: Mauger)