Strong and electroweak interactions in nuclei

Saori Pastore
NuSTEC
FNAL - Batavia IL - November 2017

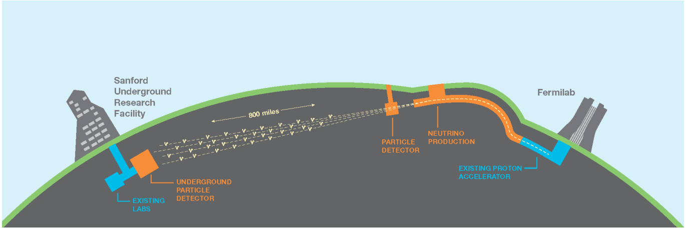
Thanks to Jorge and Luis

Motivations (Why Nuclear Physics?)

* Nuclei active material in experiments that test the SM and search for BSM physics (neutrino experiments, DM, neutrinoless double beta decay ...)

* Nuclear Physics required to *

1. Have meaningful interpretations of the data
2. Disentangle new physics from nuclear effects



LBNF

Topics (3 hours)

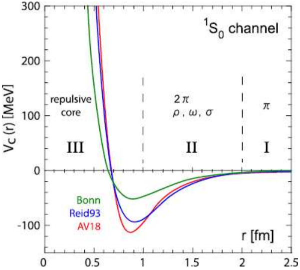
* Two- and Three-nucleon Pion Exchange Interactions ✓
* Realistic Models of Two- and Three-Nucleon Interactions ✓
* Realistic Models of Many-Body Nuclear Electroweak Currents $\sim$ ✓
* Short-range Structure of Nuclei, Nuclear Correlations, and Quasi-Elastic Scattering

The Basic Model
Requirement 1: Nuclear Interactions
DAY 1

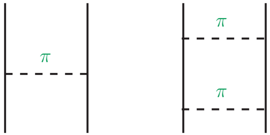
$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

Step 1. Construct two- and three-body interactions

* Chiral Effective Field Theory Interactions
* "Conventional" or "Phenomenological" Interactions



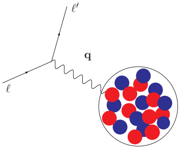
Aoki *et al.* Comput.Sci.Disc.1(2008)015009



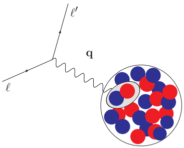
* One-pion-exchange: range$\sim \frac{1}{m_\pi} \sim 1.4$ fm
* Two-pion-exchange: range$\sim \frac{1}{2m_\pi} \sim 0.7$ fm

The Basic Model
Requirement 2: Nuclear Electromagnetic Many-Body Currents
DAY 2

1b



2b



$$
\begin{aligned}
\rho &= \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots\,, \\
\mathbf{j} &= \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots
\end{aligned}
$$

Step 2. Understand how external probes (electrons, neutrinos, DM ...) interact with nucleons, nucleon pairs, nucleon triplets...

* Chiral Effective Field Theory Electroweak Many-Body Currents
* “Conventional” or “Phenomenological” Electroweak Many-Body Currents

Step 2.a Validate and then Use the model

* Validation of the theory against Electromagnetic observables in a wide range of energies ✓
* Neutrino-Nucleus Observables from low to high energies and momenta

* In general *

- Two-body components (in the vector electromagnetic current) are essential to explain the data
- They provide up to $\sim 40\%$ contributions to magnetic moments of nuclei (static observables)
- They enhance the transverse response up $\sim 50\%$ (dynamical observables)
- One-pion-exchange currents $\mathbf{j}_\pi$, present in both formulations, provide $\sim 0.8\,\mathbf{j}_{ij}$

$\mathbf{j}_\pi$

Conclusion and Outlook II

* The Microscopic picture of the nucleus based on many-body interactions and electroweak currents successfully explains the data both qualitatively and quantitatively

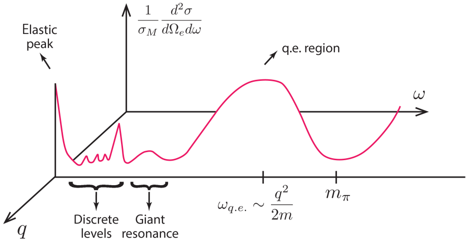
* It explains the spectra and shapes of nuclei

* It has been validated against electromagnetic observables in a wide range of energies from *keV* (relevant to astrophysics) to *GeV* (relevant to accelerator neutrino experiments)

* Two-body physics, correlations and two-body currents, is essential to understand the data both for static nuclear properties (spectra, electromagnetic moments, nuclear form factors) and dynamical properties (transitions in low-lying nuclear states, nuclear responses)

* We want the same coherent picture for interactions with neutrinos!!! *

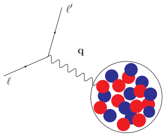
Nuclei and Neutrinos

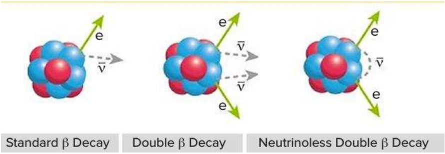


* ν-A scattering "Anomalies" the QE region

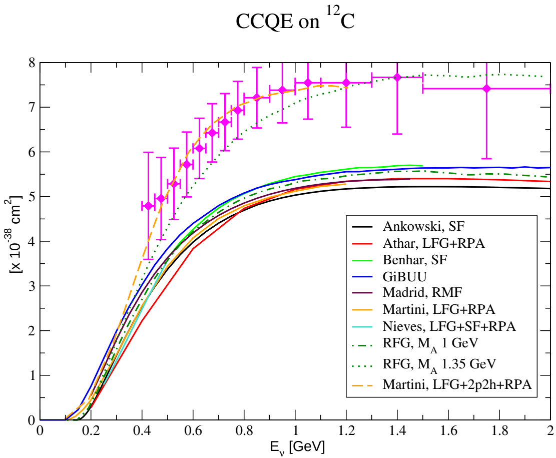
* "g_A-problem" low-values (zero) of momentum transfer

* Scarce data at moderate values of momentum transfer



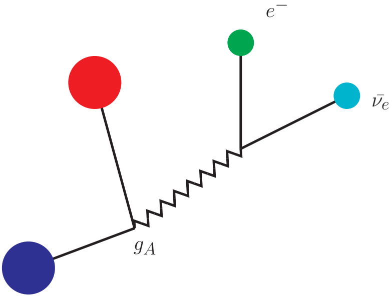


Neutrino-Nucleus scattering



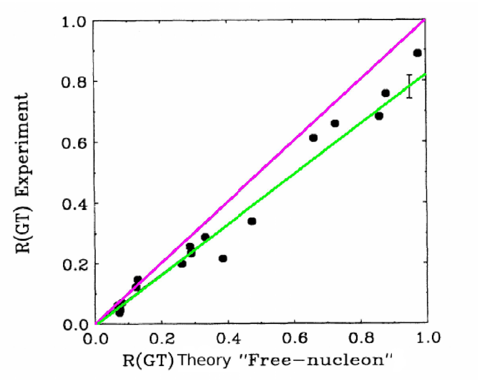
Alvarez-Ruso arXiv:1012.3871

β-decay



“Anomalies” $q \sim 0$: The “g_A problem”

Gamow-Teller Matrix Elements Theory vs Expt

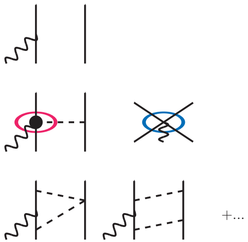


in $3 \leq \mathrm{A} \leq 18 \longrightarrow g_A^{\mathrm{eff}} \simeq 0.80\, g_A$

Chou *et al.* PRC47(1993)163

Missing Physics: 1. Correlations and/or 2. Two-body currents

Two-body Axial Currents from χEFT



A. Baroni *et al.* PRC93(2016)015501

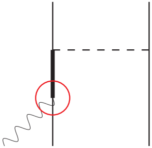
H. Krebs *et al.* Ann.Phy.378(2017)

* c_3 and c_4 are taken them from Entem and Machleidt PRC68(2003)041001 & Phys.Rep.503(2011)1
* c_D fitted to GT m.e. of tritium beta-decay Baroni *et al.* PRC94(2016)024003

* $\sim 2\%$ additive contribution from two-body currents *

A. Baroni *et al.* PRC93(2016)015501 & PRC94(2016)024003

"Conventional" Two-body Axial Currents



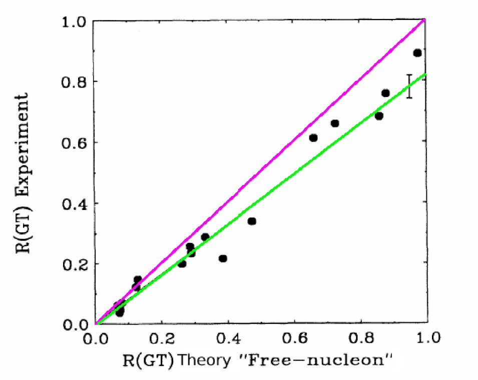
1) One body has GT, relativistic corrections, PS from pion-pole diagrams
2) Two-body currents
   2.a) Major contribution from Δ-excitation current
   2.b) Negligible contributions from $A\pi$, $A\rho$, $A\pi\rho$
3) $AN\Delta$ coupling fixed to tritium beta-decay
4) $\sim 3\%$ additive correction from Δ-current

Chemtob, Rho, Towner, Riska, Schiavilla, Marcucci …

see, e.g., Marcucci *et al.* PRC63(2001)015801 and references therein

"Anomalies" $q \sim 0$: The "g_A problem"

Gamow-Teller Matrix Elements Theory vs Expt

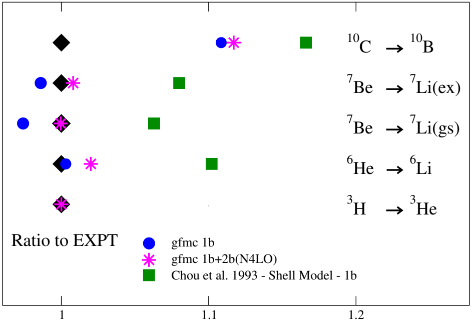


$$\text{in } 3 \leq \text{A} \leq 18 \longrightarrow g_A^{\text{eff}} \simeq 0.80\, g_A$$

Chou *et al.* PRC47(1993)163

Missing Physics: 1. Correlations and/or 2. Two-body currents

Single β-decay Matrix Elements in $A = 6$–10



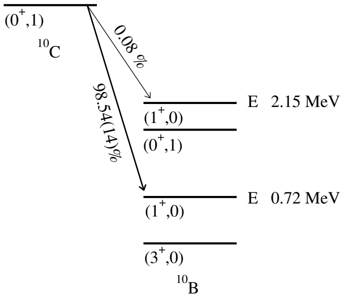
Pastore *et al.* arXiv:1709.03592

Based on $g_A \sim 1.27$ no quenching factor

* Correlations in the wave functions seem to, at least partially, solve the g_A-problem

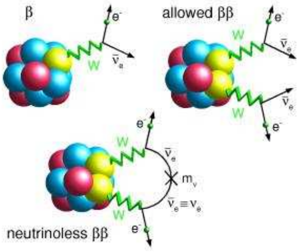
* Two-body currents are small $\sim 2\%$ $*$ data from TUNL, Suzuki *et al.* PRC67(2003)044302, Chou *et al.* PRC47(1993)163

^{10}B

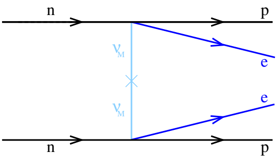


* Preliminary results based on the Chiral Effective Field Theory Potential with Δ's by Piarulli *et al.* PRC91(2015)024003-PRC94(2016)054007-arXiv:1707.02883 over predict by only 4% *

Neutrinoless double β-decay



Berna U.



Engel and Menendez Reports on Progress in Physics 80, 046301 (2017)

"The average momentum is about 100 MeV, a scale set by the average distance between the two decaying neutrons"

* Matrix Elements $\propto g_A^2$ and Decay Rates $\propto g_A^4$ *

Fundamental Physics Quests: Double Beta Decay

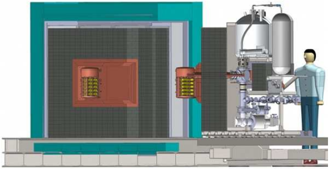
observation of $0\nu\beta\beta$-decay

$\rightarrow$

lepton # $L = l - \bar{l}$ not conserved

$\rightarrow$

implications in
matter-antimatter imbalance



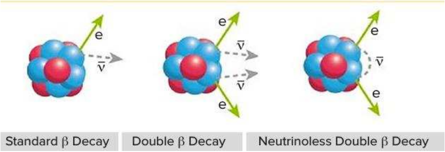
Majorana Demonstrator

* detectors' active material ^{76}Ge *

$0\nu\beta\beta$-decay $\tau_{1/2} \gtrsim 10^{25}$ years (age of the universe 1.4×10^{10} years)

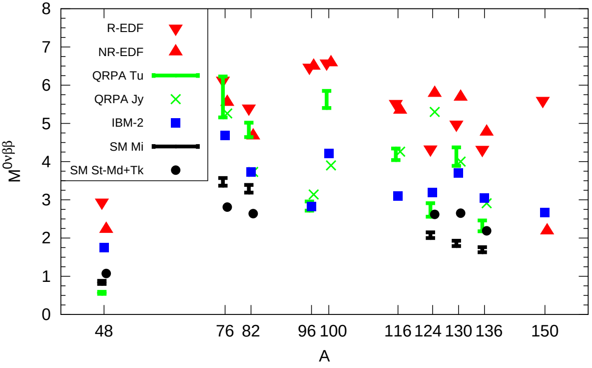
1 ton of material to see (if any) ~ 5 decays per year

* also, if nuclear m.e.'s are known, absolute ν-masses can be extracted *



2015 Long Range Plane for Nuclear Physics

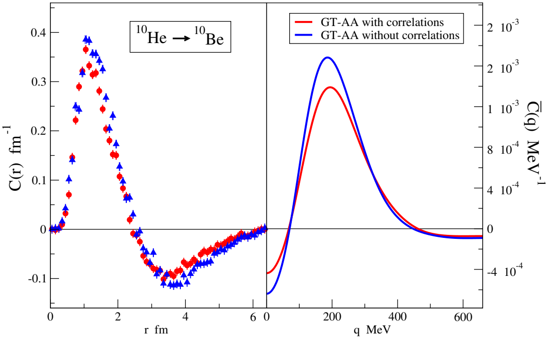
Neutrinoless double beta decay: STATUS



Javier Menendez arXiv:1703.08921

Matrix Elements Estimates differ by a factor of ~ 2

Momentum Dependence

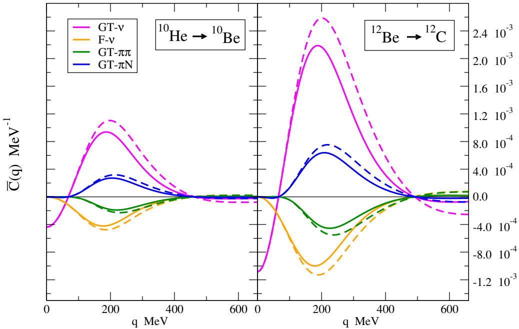


* Peaks at ~ 200 MeV
* no 'pion-exchange-like' correlations
* yes 'pion-exchange-like' correlations
* $\sim 10\%$ increase in the matrix elements corresponds to a 'g_A-quenching' of ~ 0.95
* as opposed to ~ 0.83 found in $A = 10$ single beta decay

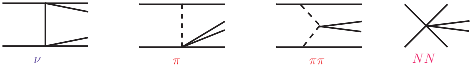
* data at moderate momenta is valuable *

Pastore, Mereghetti, Dekens, Carlson, Cirigliano, Wiringa arXiv:1710.05026

Momentum Dependence and Sensitivity to Nucleonic Form Factors

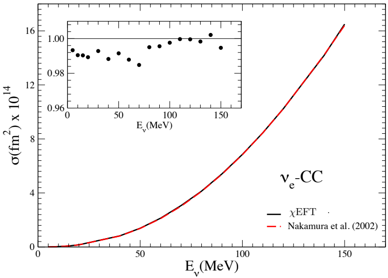


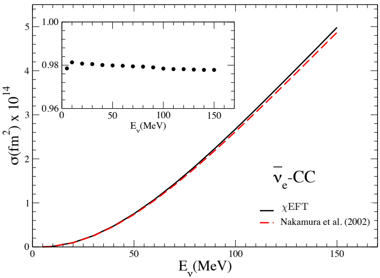
- Peaks at ~ 200 MeV
- Form factors on/off $\rightarrow \sim 10\%$ variation
- $A = 10$ highly suppressed w.r.t. $A = 12$
- $A = 12$ 'most similar' to experimental cases



Pastore, Mereghetti, Dekens, Carlson, Cirigliano, Wiringa arXiv:1710.05026

Neutrino-Deuteron Scattering



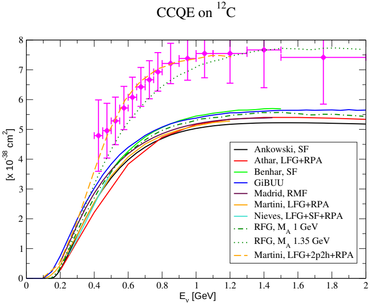


$$\nu_e + d \to p + p + e$$
$$\bar{\nu}_e + d \to n + n + e^+$$

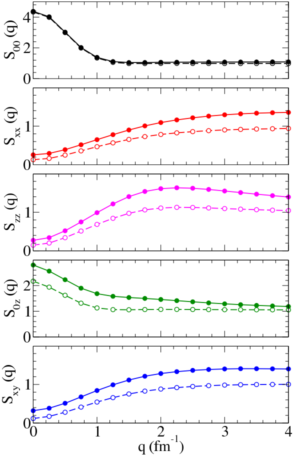
Baroni and Schiavilla Phys. Rev. C 96, 014002 (2017)
Nakamura *et al.* Nucl.Phys. A707 (2002)

Shen *et al.* Phys.Rev. C86 (2012) 035503

Recent Developments on ^{12}C: Weak Responses



Alvarez-Ruso arXiv:1012.3871



$q = [300 - 750]$ MeV

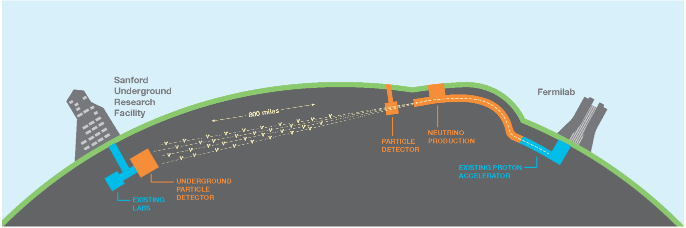
Lovato, Gandolfi *et al.* - PRL112(2014)182502

More by Alessandro Lovato

- How do nuclei interact with neutrinos in the GeV energy regime and how can calculations of these interaction cross sections be improved?

i.e.

Towards a microscopic description of the ν-A inclusive cross section:
The Short-Time-Approximation

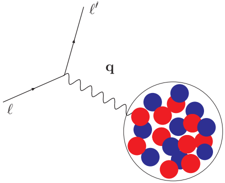


Inclusive (e,e') scattering: Intro to Short-Time-Approximation

* ν/e inclusive xsecs are completely specified by the response functions
* Two response functions for (e,e') inclusive xsec

$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle f|O_\alpha(\mathbf{q})|0\rangle|^2 \qquad \alpha = L,T$$

Longitudinal response induced by $O_L = \rho$
Transverse response induced by $O_T = \mathbf{j}$



* Sum Rules *

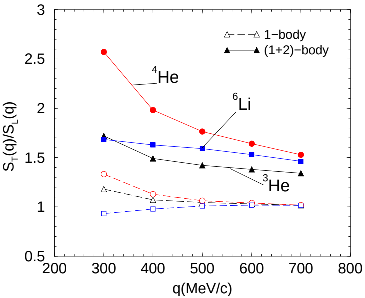
Exploit integral properties of the response functions + closure to avoid explicit calculation of the final states

$$S(q,\tau) = \int_0^\infty d\omega\, K(\tau,\omega) R_\alpha(q,\omega)$$

* Coulomb Sum Rules *

$$S_\alpha(q) = \int_0^\infty d\omega\, R_\alpha(q,\omega) \propto \langle 0|O_\alpha^\dagger(\mathbf{q}) O_\alpha(\mathbf{q})|0\rangle$$

Sum Rules and Two-body Currents: Excess Transverse Strength



Carlson *et al.* PRC65(2002)024002

$$S_T(q) \propto \langle 0|\mathbf{j}^\dagger\, \mathbf{j}|0\rangle$$
$$\propto \langle 0|\mathbf{j}_{1b}{}^\dagger\, \mathbf{j}_{1b}|0\rangle + \langle 0|\mathbf{j}_{1b}{}^\dagger\, \mathbf{j}_{2b}|0\rangle + \dots$$

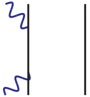
- $\mathbf{j} = \mathbf{j}_{1b} + \mathbf{j}_{2b}$

• enhancement of the transverse response is due to interference between 1b and 2b currents AND presence of two-nucleon correlations •

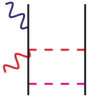
Important:

To see enhancement you need BOTH two-body currents and two-body correlations (another effect of the continuity equation)

Carlson at latest INT neutrino workshop Dec. 2016



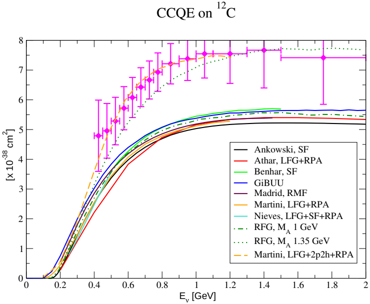
$\langle \mathbf{j}_{1b}^\dagger\ \ \mathbf{j}_{1b}\rangle\ > 0$



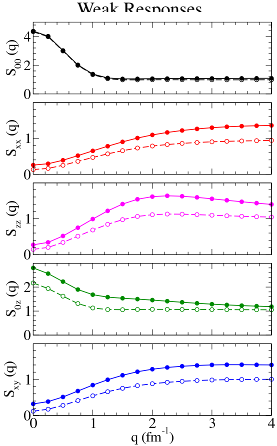
$\langle \mathbf{j}_{1b}^\dagger\ \mathbf{j}_{2b}\ v_\pi\rangle \propto \langle v_\pi^2\rangle\ > 0$

Recent Developments on ^{12}C
Quantum Monte Carlo Calculations of Nuclear Responses and Sum Rules

Charge-Current Cross Section



Alvarez-Ruso arXiv:1012.3871



$q = [300 - 750]$ MeV

Lovato *et al.* PRC91(2015)062501 + arXiv:1605.00248

$\sim$ 100 million core hours

CHALLENGE:

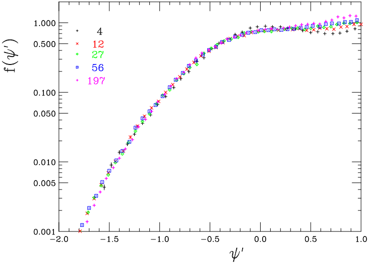
How do we describe electroweak-scattering off $A > 12$ nuclei

without loosing two-body physics?

Scaling properties of the Response Functions

Inclusive xsec depends on a single (scaling) function of ω and q

Scaling 2$^{\text{nd}}$ kind: independence form A

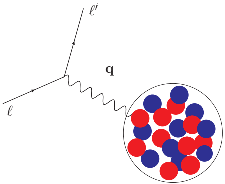


Donnelly and Sick - PRC60(1999)065502

1. Rely on observed scaling properties of inclusive xsecs, universal behavior of nucleon/A momentum distributions, and exhibited locality of nuclear properties to build approximate response functions for $A > 12$ nuclei
2. From exact *ab initio* calculations we know that two-body correlations and two-body currents are crucial
3. Build a model that retains two-body physics

In PWIA:

Response functions given by incoherent scattering off single nucleons that propagate freely in the final state (plane waves)



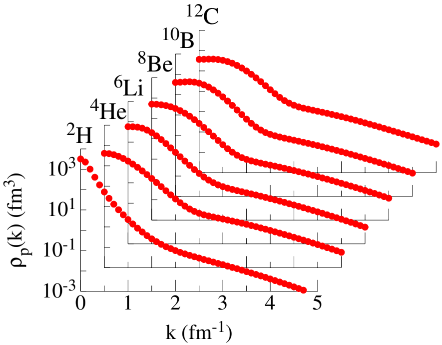
$$R_{\alpha}(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) \langle 0|O_{\alpha}^{\dagger}(\mathbf{q})|f\rangle\langle f|O_{\alpha}(\mathbf{q})|0\rangle$$

$$O_{\alpha}(\mathbf{q}) = O_{\alpha}^{(1)}(\mathbf{q}) = \text{1b}$$
$$|f\rangle \sim e^{i(\mathbf{k}+\mathbf{q})\cdot\mathbf{r}} = \text{free single nucleon w.f.}$$

* PWIA Longitudinal Response in terms of the p-momentum distribution $n_p(\mathbf{k})$ *

$$R_L^{\text{PWIA}}(q,\omega) = \int d\mathbf{k}\, n_p(\mathbf{k})\delta\left(\omega - \frac{(\mathbf{k}+\mathbf{q})^2}{2m_N} + \frac{\mathbf{k}^2}{2m_N}\right)$$
$$O_L^{(1)}(\mathbf{q}) = e\sum_{i=1}^{A} \frac{1+\tau_{i,z}}{2}\, e^{i\mathbf{q}\cdot\mathbf{r}_i}$$

Proton Momentum Distributions



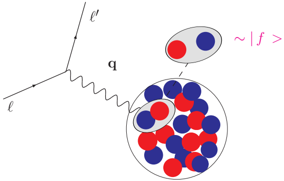
Wiringa *et al.* - PRC89(2014)024305

1-body momentum distributions http://www.phy.anl.gov/theory/research/momenta/
2-body momentum distributions http://www.phy.anl.gov/theory/research/momenta2/

The Short-Time Approximation - STA

In STA:

Response functions are given by the scattering off pairs of fully interacting nucleons that propagate into a correlated pair of nucleons



$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) \langle\, 0|O_\alpha^\dagger(\mathbf{q})|f\rangle\langle f|O_\alpha(\mathbf{q})|0\,\rangle$$

$$O_\alpha(\mathbf{q}) = O_\alpha^{(1)}(\mathbf{q}) + O_\alpha^{(2)}(\mathbf{q}) = 1\mathrm{b} + 2\mathrm{b}$$

$$|f\rangle \sim |\psi_{p,P,J,M,L,S,T,M_T}(r,R)\rangle = \text{correlated two} - \text{nucleon w.f.}$$

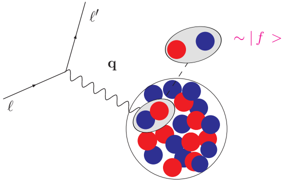
* We retain two-body physics consistently in the nuclear interactions and electroweak currents

* $R_\alpha(q,\omega)$ requires only direct calculation of g.s. $|0\rangle$ w.f.'s *

* STA can be implemented to accommodate for more two-body physics, *e.g.*, pion-production induced by e and ν

The Short-Time Approximation

In STA:



Response functions are given by the scattering off pairs of fully interacting nucleons that propagate into a correlated pair of nucleons

$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) \langle 0|O_\alpha^\dagger(\mathbf{q})|f\rangle\langle f|O_\alpha(\mathbf{q})|0\rangle$$

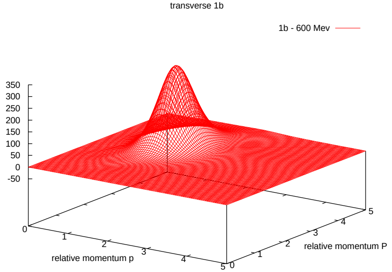
$$O_\alpha(\mathbf{q}) = O_\alpha^{(1)}(\mathbf{q}) + O_\alpha^{(2)}(\mathbf{q}) = 1\mathrm{b} + 2\mathrm{b}$$

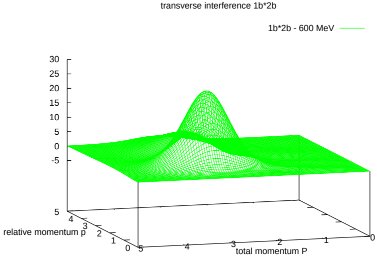
$|f\rangle$ is a function of $\mathbf{p}$ and $\mathbf{P}$ e.g. for free propagator $\sim e^{i\mathbf{p}\cdot\mathbf{r}} e^{i\mathbf{P}\cdot\mathbf{R}}$

$|f\rangle \sim |\psi_{p,P,J,M,L,S,T,M_T}(r,R)\rangle =$ correlated two $-$ nucleon w.f.

$$R_\alpha(q,\omega) \sim \int \delta\left(\omega + E_0 - E_f\right) d\Omega_P\, d\Omega_p\, dP\, dp \left[p^2 P^2 \langle 0|O_\alpha^\dagger(\mathbf{q})|\mathbf{p},\mathbf{P}\rangle\langle \mathbf{p},\mathbf{P}|O_\alpha(\mathbf{q})|0\rangle\right]$$

The Short-Time Approximation

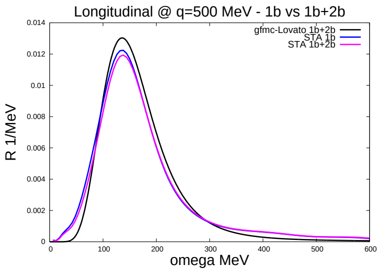


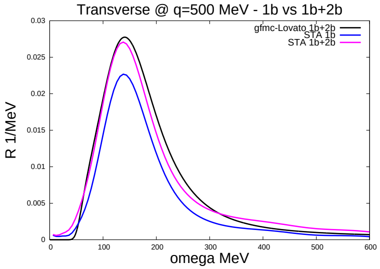


300 core hours with 1b + 2b for ^4He

Preliminary results

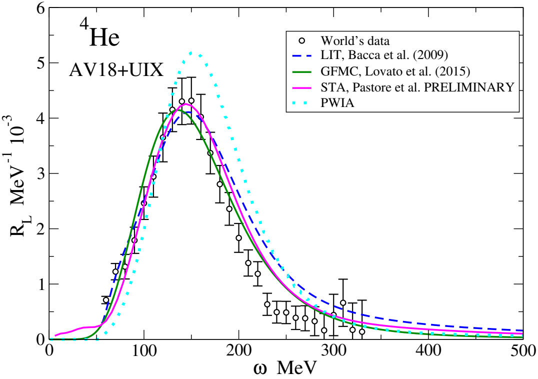
1b vs 1b+2b





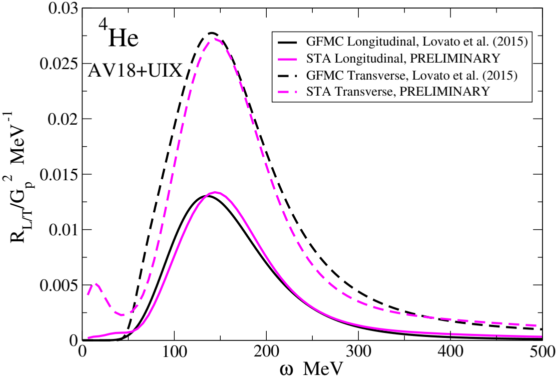
Preliminary results

The Short-Time Approximation



Longitudinal Response function at $q = 500$ MeV

Preliminary results



Longitudinal vs Transverse Response Function at $q = 500$ MeV

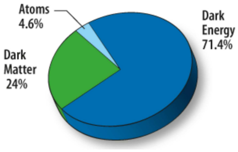
Preliminary results

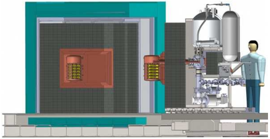
Conclusion and Outlook III

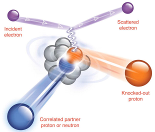
* We are constructing a coherent picture of neutrino-nucleus interactions spanning a wide rage of energy and momenta
* Many-body correlations contribute to explain the "g_A-problem" at low-momenta (zero)
* Studies on neutrinoless double beta decay indicate a less severe "g_A-problem" at moderate values of momentum transfer
* Important to validate the theory at moderate values of momentum transfer
* Two-body physics, correlations and two-body currents, play a crucial role in the explanation of electromagnetic responses of nuclei
* Microscopic Calculations of weak response indicate that two-body physics important in electroweak responses More by Alessandro Lovato
* We are addressing how to retain two-body physics in approximated Microscopic calculations of responses in $A > 12$ nuclei - This is the STA
* Benchmark between STA and GFMC exact calculations by Lovato *et al.* is excellent

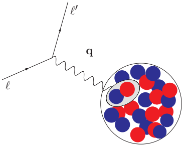
* All this work impacts on Fundamental Physics Quests! *

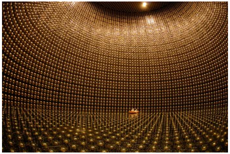
Outlook

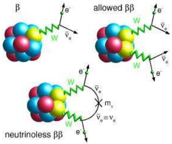


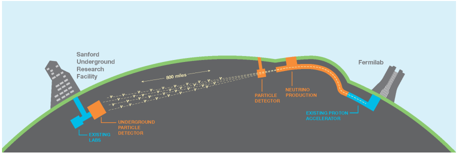












$\langle \mathbf{j}_{1b}^{\dagger} \; \mathbf{j}_{1b} \rangle \; > 0$

$\langle \mathbf{j}_{1b}^{\dagger} \; \mathbf{j}_{2b} \; v_{\pi} \rangle \propto \langle v_{\pi}^{2} \rangle \; > 0$

It always seems impossible until it's done

* Thank you all for the questions and interesting discussions

* Thank you organizers

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June 12 - July 13, 2018
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EXTRA SLIDES