Few-Body Physics with Relation to Neutrinos

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HUGS Summer School

Jefferson Lab - Newport News VA, June 2018

Thanks to the Organizers

Neutrinos (Fundamental Symmetries) and Nuclei

Topics (5 hours)

* Nuclear Theory for the Neutrino Experimental Program ✓
* Microscopic (or *ab initio*) Description of Nuclei ✓
* "Realistic" Models of Two- and Three-Nucleon Interactions $\sim$ ✓
* "Realistic" Models of Many-Body Nuclear Electroweak Currents
* Short-range Structure of Nuclei and Nuclear Correlations
* Quasi-Elastic Electron and Neutrino Scattering off Nuclei
* Validation of the theory against available data

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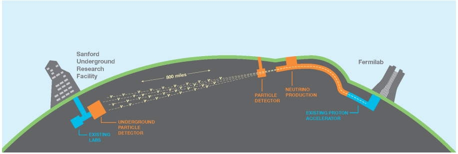
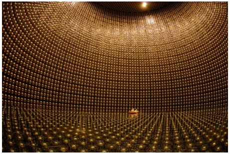
Nuclei for Accelerator Neutrinos' Experiments

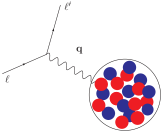


LBNF



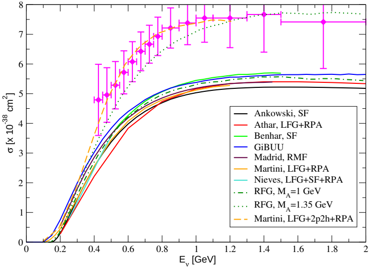
T2K

Neutrino-Nucleus scattering



$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2 \left(\frac{\Delta m_{21}^2 L}{2E_\nu}\right)$$

CCQE on ^{12}C

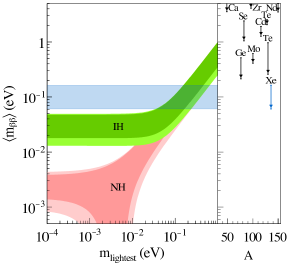


Alvarez-Ruso arXiv:1012.3871

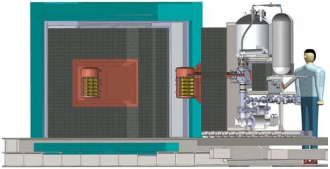
* Nuclei of ^{12}C, ^{40}Ar, ^{16}O, ^{56}Fe, ... *

are the DUNE, MiniBoone, T2K, Minerνa ... detectors' active material

Nuclear Physics for Neutrinoless Double Beta Decay Searches



J. Engel and J. Menéndez - arXiv:1610.06548

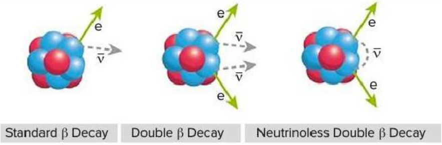


Majorana Demonstrator

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

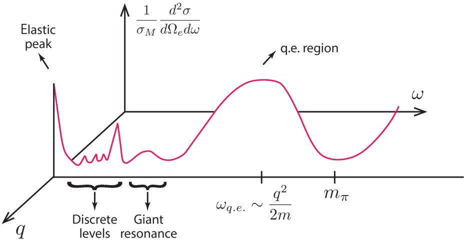
need 1 ton of material to see (if any) $\sim$ 5 decays per year

* Decay Rate $\propto$ (nuclear matrix elements)$^2 \times \langle m_{\beta\beta} \rangle^2$ *

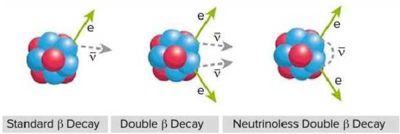


2015 Long Range Plane for Nuclear Physics

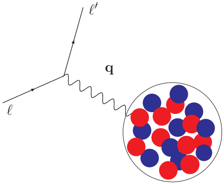
Nuclear Structure and Dynamics



- $\omega \sim$ few MeV, $q \sim 0$: EM decay, β-decay, $\beta\beta$-decays
- $\omega \lesssim$ tens MeV: Nuclear Rates for Astrophysics
- $\omega \sim 10^2$ MeV: Accelerator neutrinos, ν-nucleus scattering



The Microscopic (or *ab initio*) Description of Nuclei



Develop a comprehensive theory that describes quantitatively and predictably all nuclear structure and reactions

* Accurate understanding of interactions between nucleons, p's and n's

* and between e's, ν's, **DM**, ..., with nucleons, nucleons-pairs, ...

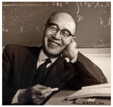
$$H\Psi = E\Psi$$

$$\Psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A, s_1, s_2, \ldots, s_A, t_1, t_2, \ldots, t_A)$$

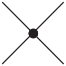
Erwin Schrödinger

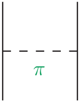
Nuclear Force These Days

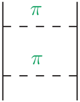
* 1930s Yukawa Potential
* 1960–1990 Highly sophisticated meson exchange potentials
* 1990s– Highly sophisticated Chiral Effective Field Theory based potentials



Hideki Yukawa



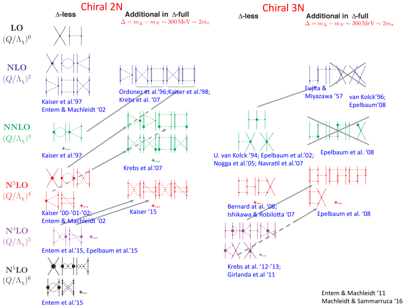




Steven Weinberg

* Contact terms: short-range
* One-pion-exchange: range$\sim \frac{1}{m_\pi}$
* Two-pion-exchange: range$\sim \frac{1}{2m_\pi}$

Nuclear Interactions and the role of the Δ



Courtesy of Maria Piarulli

* N3LO with Δ nucleon-nucleon interaction constructed by
Piarulli *et al.* in PRC91(2015)024003-PRC94(2016)054007-arXiv:1707.02883 with $\Delta's$
fits ~ 2000 (~ 3000) data up 125 (200) MeV with χ^2/datum ~ 1;
* N2LO with Δ 3-nucleon force fits ^{3}H binding energy and the *nd* scattering length

$$\upsilon_{12} = \sum_p \upsilon_{12}^p(r) O_{12}\,; \quad O_{12} = [1, \boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2, S_{12}, \mathbf{L}\cdot\mathbf{S}, \mathbf{L}^2, \mathbf{L}^2\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2, (\mathbf{L}\cdot\mathbf{S})^2] \otimes [1, \boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2]$$

+ operators 4 terms breaking charge independence

Phenomenological aka Conventional aka Traditional aka Realistic Two- and Three- Nucleon Potentials

NUCLEAR HAMILTONIAN

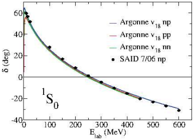
$$H = \sum_i K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

K_i: Non-relativistic kinetic energy, m_n-m_p effects included

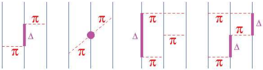
Argonne v_{18}: $v_{ij} = v^{\gamma}_{ij} + v^{\pi}_{ij} + v^{I}_{ij} + v^{S}_{ij} = \sum v_p(r_{ij}) O^p_{ij}$

- 18 spin, tensor, spin-orbit, isospin, etc., operators
- full EM and strong CD and CSB terms included
- predominantly local operator structure
- fits Nijmegen PWA93 data with χ^2/d.o.f.=1.1

Wiringa, Stoks, & Schiavilla, PRC **51**, (1995)



Urbana & Illinois: $V_{ijk} = V^{2\pi}_{ijk} + V^{3\pi}_{ijk} + V^{R}_{ijk}$



- Urbana has standard 2π P-wave + short-range repulsion for matter saturation
- Illinois adds 2π S-wave + 3π rings to provide extra T=3/2 interaction
- Illinois-7 has four parameters fit to 23 levels in $A \leq 10$ nuclei

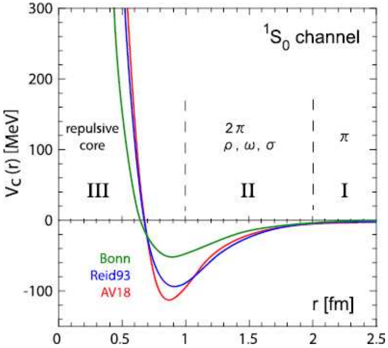
Pieper, Pandharipande, Wiringa, & Carlson, PRC **64**, 014001 (2001)
Pieper, AIP CP **1011**, 143 (2008)

Courtesy of Bob Wiringa

* AV18 fitted up to 350 MeV, reproduces phase shifts up to $\sim$ 1 GeV *

* IL7 fitted to 23 energy levels, predicts hundreds of levels *

Nucleon-nucleon potential



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

CT = Contact Term* - short-range;
OPE = One Pion Exchange - range $\sim \frac{1}{m_\pi}$;
TPE = Two Pion Exchange - range $\sim \frac{1}{2m_\pi}$

$*$ in practice CT's in r-space are coded with representations of a δ-function (*e.g.*, a Gaussian function), or special functions such as Wood-Saxon functions

ρ, ω, σ-exchange

The One Boson Exchange (OBE) Lagrangians

scalar

$$-g^{S0}\bar{\psi}\psi\phi^{S0} \qquad -g^{S1}\bar{\psi}\tau\psi\cdot\vec{\phi}^{S1}$$

pseudo-scalar

$$-ig^{PS0}\bar{\psi}\gamma_5\psi\phi^{PS0} \qquad -ig^{PS1}\bar{\psi}\gamma_5\tau\psi\cdot\vec{\phi}^{PS1}$$

vector

$$-g^{V0}\bar{\psi}\gamma^{\mu}\psi\phi^{V0}{}_{\mu} \qquad -g^{V1}\bar{\psi}\gamma^{\mu}\tau\psi\cdot\vec{\phi}^{V1}{}_{\mu}$$

tensor

$$\frac{-g^{T0}}{2m^{T0}}\bar{\psi}\sigma^{\mu\nu}\psi\partial_{\nu}\phi^{T0}_{\mu} \qquad \frac{-g^{T1}}{2m^{T1}}\bar{\psi}\sigma^{\mu\nu}\tau\psi\cdot\partial_{\nu}\vec{\phi}^{T1}_{\mu}$$

slide from my 15 mins HUGS talk...

CD Bonn Potential

	Mass (MeV)	I	J^π	$\frac{g^2}{4\pi}$	$\frac{g^T}{g_V}$	
$\pi^\pm$	139.56995	1	0^-	13.6		$PS1$
π^0	134.9764	1	0^-	13.6		$PS1$
η	547.3	0	0^-	0.4		$PS0$
$\rho^\pm, \rho^0$	769.9	1	1^-	0.84	6.1	$V1$; $T1$
ω	781.94	0	1^-	20.0	0.0	$V0$; $T0$
σ	400-1200	0	0^+			$S0$

R.Machleidt, Phys.Rev. C**63**, 014001 (2001)

$$O_{12} = [1, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2, S_{12}, \mathbf{L} \cdot \mathbf{S}] \otimes [1, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2]$$

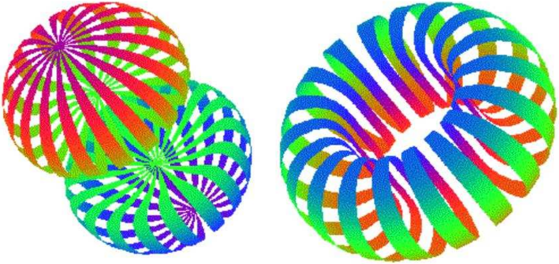
vs

$$O_{12} = [1, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2] \otimes [1, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2]; S_{12} \mathrm{from}\, 2\pi - \mathrm{exchange}$$

slide from my 15 mins HUGS...

Nucleon-Nucleon Potential and the Deuteron

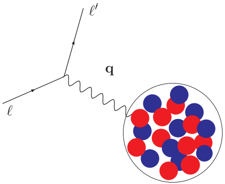
$M = \pm 1$ $\qquad$ $M = 0$



Constant density surfaces for a polarized deuteron in the $M = \pm 1$ (left) and $M = 0$ (right) states

Carlson and Schiavilla Rev.Mod.Phys.70(1998)743

Quantum Monte Carlo Methods



Solve numerically the many-body problem

$$H\Psi = E\Psi$$

$$\Psi(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_A, s_1, s_2, ..., s_A, t_1, t_2, ..., t_A)$$

Ψ are spin-isospin vectors in $3A$ dimensions with $2^A \times \frac{A!}{Z!(A-Z)!}$ components

^{4}He : 96
^{6}Li : 1280
^{8}Li : 14336
^{12}C : 540572

Variational Monte Carlo (VMC)

Minimize expectation value of H = T + AV18 + IL7

$$E_V = \frac{\langle \Psi_V | H | \Psi_V \rangle}{\langle \Psi_V | \Psi_V \rangle} \geq E_0$$

using trial function

$$|\Psi_V\rangle = \left[\mathscr{S} \prod_{i<j} (1 + U_{ij} + \sum_{k \neq i,j} U_{ijk}) \right] \left[\prod_{i<j} f_c(r_{ij}) \right] |\Phi_A(JMTT_3)\rangle$$

* single-particle $\Phi_A(JMTT_3)$ is fully antisymmetric and translationally invariant
* central pair correlations $f_c(r)$ keep nucleons at favorable pair separation
* pair correlation operators U_{ij} reflect influence of v_{ij} (AV18)
* triple correlation operators U_{ijk} reflect the influence of V_{ijk} (IL7)

Lomnitz-Adler, Pandharipande, and Smith NPA361(1981)399

Wiringa, PRC43(1991)1585

Ψ_V can be further improved by "filtering" out the remaining excited state contamination

$$\Psi(\tau) = \exp[-(H - E_0)\tau]\Psi_V = \sum_n \exp[-(E_n - E_0)\tau] a_n \psi_n$$

$$\Psi(\tau \to \infty) = a_0 \psi_0$$

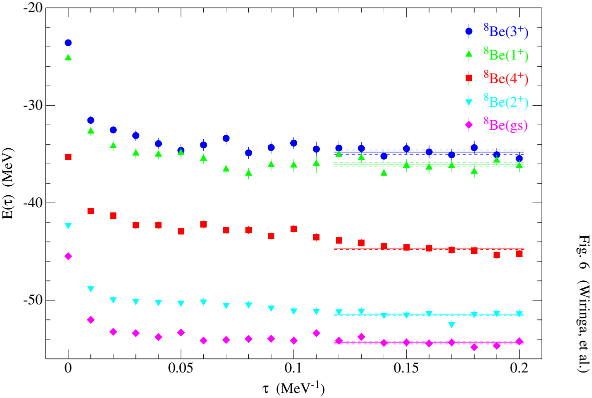
In practice, we evaluate a "mixed" estimates

$$\langle O(\tau) \rangle = \frac{{}_f\langle \Psi(\tau)|O|\Psi(\tau)\rangle_i}{\langle \Psi(\tau)|\Psi(\tau)\rangle} \approx \langle O(\tau)\rangle^i_{\text{Mixed}} + \langle O(\tau)\rangle^f_{\text{Mixed}} - \langle O \rangle_V$$

$$\langle O(\tau)\rangle^i_{\text{Mixed}} = \frac{{}_f\langle \Psi_V|O|\Psi(\tau)\rangle_i}{{}_f\langle \Psi_V|\Psi(\tau)\rangle_i} \; ; \; \langle O(\tau)\rangle^f_{\text{Mixed}} = \frac{{}_f\langle \Psi(\tau)|O|\Psi_V\rangle_i}{{}_f\langle \Psi(\tau)|\Psi_V\rangle_i}$$

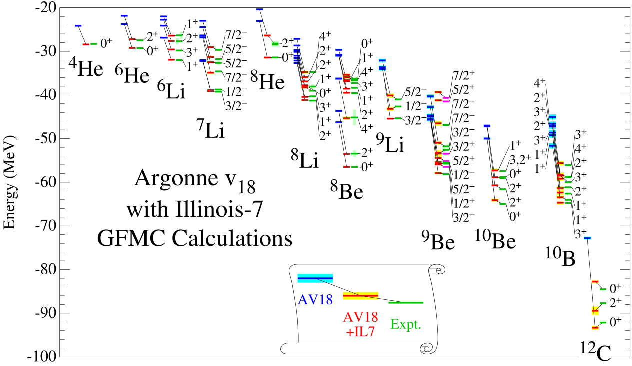
Pudliner, Pandharipande, Carlson, Pieper, & Wiringa, PRC **56**, 1720 (1997)
Wiringa, Pieper, Carlson, & Pandharipande, PRC **62**, 014001 (2000)
Pieper, Wiringa, & Carlson, PRC **70**, 054325 (2004)

GFMC Energy calculation: An example



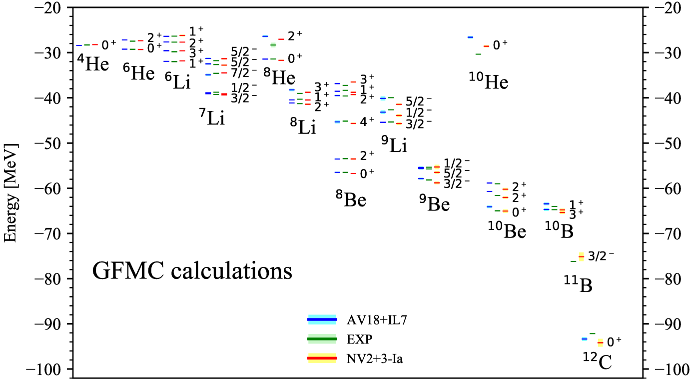
Wiringa *et al.* PRC62(2000)014001

Spectra of Light Nuclei



Carlson *et al.* Rev.Mod.Phys.87(2015)1067

Spectra of Light Nuclei



M. Piarulli *et al.* - arXiv:1707.02883

* one-pion-exchange physics dominates *
* it is included in both chiral and "conventional" potentials *

Three-body forces

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

$$V_{ijk} \sim (0.2 - 0.9)\, v_{ij} \sim (0.15 - 0.6)\, H$$

$$v_\pi \sim 0.83\, v_{ij}$$

^{10}B VMC code output

```
Ti + Vij =  -38.2131 (0.1433)          + Vijk =  -46.7975 (0.1150)

Ti   = 290.3220 (1.2932)  Vij  =-328.5351 (1.1983)  Vijk =  -8.5844 (0.0892)
```

Two-body physics dominates!

(Very) Incomplete List of Credits and Reading Material

- Pieper and Wiringa; Ann.Rev.Nucl.Part.Sci.51(2001)53
- Carlson *et al.*; Rev.Mod.Phys.87(2015)1067
- van Kolck *et al.*; PRL72(1994)1982-PRC53(1996)2086
- Kaiser, Weise *et al.*; NPA625(1997)758-NPA637(1998)395
- Epelbaum, Glöckle, Meissner*; RevModPhys81(2009)1773 and references therein
- Entem and Machleidt*; PhysRept503(2011)1 and references therin

* NN Potentials suited for Quantum Monte Carlo calculations *

- Pieper and Wiringa; Ann.Rev.Nucl.Part.Sci.51(2001)53
- Gezerlis *et al.* and Lynn *et al.*; PRL111(2013)032501,PRC90(2014)054323,PRL113(2014)192501;
- Piarulli *et al.*; PRC91(2015)024003-PRC94(2016)054007-arXiv:1707.02883

Summary: Nuclear Interactions

* The Microscopic description of Nuclei is very successful
* Nuclear two-body forces are constrained by large database of nucleon-nucleon scattering data
* Intermediate– and long–range components are described in terms of one- and two-pion exchange potentials
* Short-range parts are described by contact terms or special functions
* Due to a cancellation between kinetic and two-body contribution, three-body potentials are (small but) necessary to reach (excellent) agreement with the data
* Calculated spectra of light nuclei are reproduced within $1-2\%$ of expt data
* Two-body one-pion-exchange contributions dominate and are crucial to explain the data

Neutrinos (Fundamental Symmetries) and Nuclei

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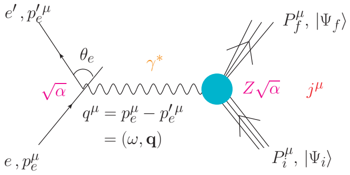
* Microscopic (or *ab initio*) Description of Nuclei ✓
* "Realistic" Models of Two- and Three-Nucleon Interactions ✓
* "Realistic" Models of Many-Body Nuclear Electroweak Currents
* Short-range Structure of Nuclei and Nuclear Correlations
* Quasi-Elastic Electron and Neutrino Scattering off Nuclei
* Validation of the theory against available data

Jefferson Lab

Electromagnetic Probes as tool to test theoretical models



* coupling constant $\alpha \sim 1/137$ allows for a perturbative treatment of the EM interaction; single photon γ exchange suffices

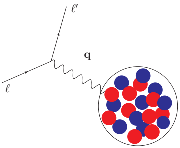
* calculated x-sections factorize into a part $\propto |\langle\Psi_f|j^{\mu}|\Psi_i\rangle|^2$ with j^{μ} nuclear EM currents and a part completely specified by the electron kinematic variables

* EXPT data are (in most cases) known with great accuracy providing stringent constraints on theories

* For light nuclei, the many-body problem can be solved exactly or within controlled approximations

Nuclear Currents: One Body Component

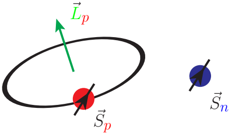
1b



$$\rho = \sum_{i=1}^{A} \rho_i + \ldots \,,$$

$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \ldots$$

* Nuclear currents given by the sum of p's and n's currents, one-body currents (1b)

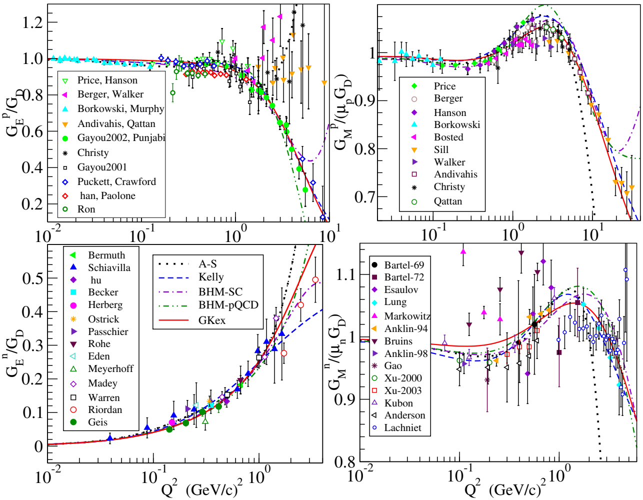


* Nucleonic electroweak form factors are taken from experimental data, and, in principle, from LQCD calculations where data are poor or scarce (*e.g.*, nucleonic axial form factor)

* A description based on 1b operators alone fails to reproduce "basic" observables (magnetic moments, *np* radiative capture)

* corrections from two-body meson-exchange currents are required to explain, *e.g.*, radiative capture Riska&Brown 1972

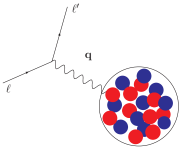
Electromagnetic Nucleonic Form Factors



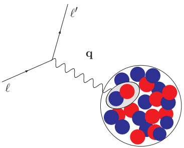
González-Jiménez Phys.Rept.524(2013)1-35

Nuclear Currents: Two-Body Component

1b



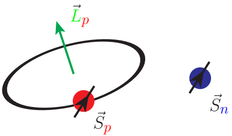
2b



$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots\,,$$

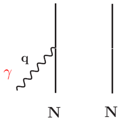
$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$

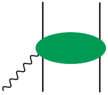
* Nuclear currents given by the sum of p's and n's currents, one-body currents (1b)



* Two-body currents (2b) essential to satisfy current conservation

* We use MEC (SNPA) or χEFT currents



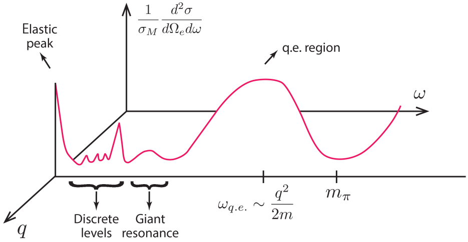


$+ \ldots$

$$\mathbf{q} \cdot \mathbf{j} = [H, \rho] = \left[t_i + v_{ij} + V_{ijk}, \rho\right]$$

$$\nabla \cdot \mathbf{j} = -\frac{\partial \rho}{\partial t} \text{ classically}$$

Electromagnetic Reactions



* $\omega \sim$ few MeV, $q \sim 0$: EM-decays
* $\omega \sim 10^2$ MeV: e-nucleus scattering

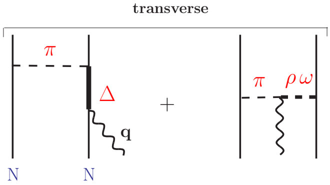
A coherent and accurate picture of the way electrons interact with nuclei in a wide range of energy and momenta exists, provided that two-body correlations and two-body currents are accounted for!

Electromagnetic Currents from Nuclear Interactions

$$\mathbf{q}\cdot\mathbf{j} = [H, \rho] = [t_i + v_{ij} + V_{ijk}, \rho]$$

1) Longitudinal component fixed by current conservation
2) Plus transverse "phenomenological" terms

$$\mathbf{j} = \mathbf{j}^{(1)} + \mathbf{j}^{(2)}(v) + \mathbf{j}^{(3)}(V) + \ldots$$

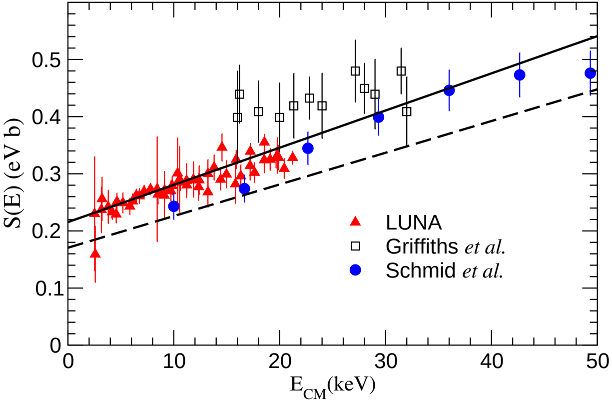


Villars, Myiazawa (40-ies), Chemtob, Riska, Schiavilla …
see, *e.g.*, Marcucci *et al.* PRC**72**(2005)014001 and references therein

Currents from nuclear interactions

Satisfactory description of a variety of nuclear em properties in $A \leq 12$

^{2}H(p,γ)^{3}He capture



Marcucci *et al.* PRC**72**, 014001 (2005)

Currents from χEFT - Time-Ordered-Perturbation Theory

The relevant degrees of freedom of nuclear physics are bound states of QCD

* non relativistic nucleons N
* pions π as mediators of the nucleon-nucleon interaction
* non relativistic Delta's Δ with $m_\Delta \sim m_N + 2m_\pi$

Transition amplitude in time-ordered perturbation theory

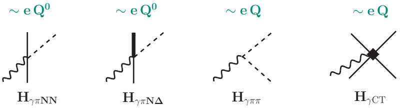
$$T_{fi} = \langle N'N' \mid H_1 \sum_{n=1}^{\infty} \left(\frac{1}{E_i - H_0 + i\eta} H_1 \right)^{n-1} \mid NN \rangle^*$$

H_0 = free π, N, Δ Hamiltonians
H_1 = interacting π, N, Δ, and external electroweak fields Hamiltonians

$$T_{fi} = \langle N'N' \mid T \mid NN \rangle \propto v_{ij} \,, \qquad T_{fi} = \langle N'N' \mid T \mid NN; \gamma \rangle \propto (A^0 \rho_{ij}, \mathbf{A} \cdot \mathbf{j}_{ij})$$

* $A^\mu = (A^0, \mathbf{A})$ photon field

External Electromagnetic Field



"Minimal" Electromagnetic Vertices

* EM H_1 obtained by minimal substitution in the π- and N-derivative couplings (same as doing $\mathbf{p} \to \mathbf{p} + e\,\mathbf{A}$, minimal coupling)

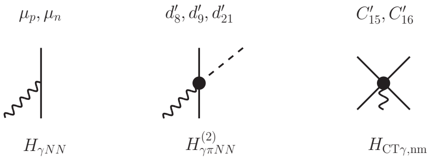
$$\nabla \pi_{\mp}(\mathbf{x}) \quad \to \quad [\nabla \mp i e \mathbf{A}(\mathbf{x})]\, \pi_{\mp}(\mathbf{x})$$

$$\nabla N(\mathbf{x}) \quad \to \quad [\nabla - i e\, e_N \mathbf{A}(\mathbf{x})]\, N(\mathbf{x}) \;, \qquad e_N = (1+\tau_z)/2$$

* same LECs as the Strong Vertices *

* This is equivalent to say that the currents are conserved, *i.e.*, the continuity equation is satisfied

External Electromagnetic Field



“Non-Minimal” Electromagnetic Vertices

* EM H_1 involving the tensor field $F_{\mu\nu} = (\partial_\mu A_\nu - \partial_\nu A_\mu)$

LECs are not constrained by the strong interaction
there are additional LECs fixed to EM observables

* $H_{\gamma NN}$ obtained by non-relativistic reduction of the covariant single nucleon currents constrained to $\mu_p = 2.793$ n.m. and $\mu_n = -1.913$ n.m.

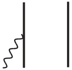
* $H_{\gamma\pi NN}$ involves $\nabla\pi$ and ∇N and 3 new LECs (2 of them “mimicking” Δ)

* $H_{CT2\gamma}$ involves 2 new LECs

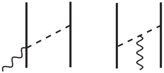
* These are the so called the “transverse” currents

EM Currents $\mathbf{j}$ from Chiral Effective Field Theory

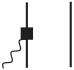
LO : $\mathbf{j}^{(-2)} \sim \mathbf{eQ^{-2}}$



NLO : $\mathbf{j}^{(-1)} \sim \mathbf{eQ^{-1}}$



N^{2}LO : $\mathbf{j}^{(-0)} \sim \mathbf{eQ^{0}}$



* Note that $\mathbf{j}_\pi$ satisfies the continuity equation with υ_π (can be done analytically)

$$\upsilon_\pi(\mathbf{k}) = -\frac{g_A^2}{F_\pi^2}\frac{\boldsymbol{\sigma}_1\cdot\mathbf{k}\,\boldsymbol{\sigma}_2\cdot\mathbf{k}}{\omega_k^2}\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2$$

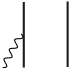
$$\mathbf{j}_\pi(\mathbf{k}_1,\mathbf{k}_2) = -ie\frac{g_A^2}{F_\pi^2}(\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2)_z\boldsymbol{\sigma}_1\frac{\boldsymbol{\sigma}_2\cdot\mathbf{k}_2}{\omega_{k_2}^2} + 1 \rightleftharpoons 2$$

$$+ \quad ie\frac{g_A^2}{F_\pi^2}(\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2)_z\frac{\mathbf{k}_1-\mathbf{k}_2}{\omega_{k_1}^2\,\omega_{k_2}^2}\boldsymbol{\sigma}_1\cdot\mathbf{k}_1\,\boldsymbol{\sigma}_2\cdot\mathbf{k}_2$$

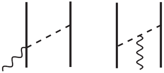
* LO = one-body current *

EM Currents **j** from Chiral Effective Field Theory

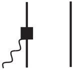
LO : $\mathbf{j}^{(-2)} \sim \mathbf{eQ^{-2}}$



NLO : $\mathbf{j}^{(-1)} \sim \mathbf{eQ^{-1}}$



N^{2}LO : $\mathbf{j}^{(-0)} \sim \mathbf{eQ^{0}}$



N^{3}LO: $\mathbf{j}^{(1)} \sim \mathbf{eQ}$

unknown LEC′s →

No three-body currents at this order!

* Analogue expansion exists for the Time Component (Charge Operator) ρ

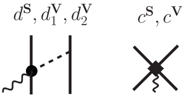
* Two-body corrections to the one-body Charge Operator appear at N3LO

Pastore *et al.* PRC78(2008)064002 & PRC80(2009)034004 & PRC84(2011)024001

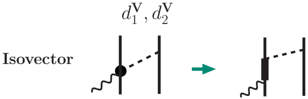
* analogue expansion exists for the Axial nuclear current - Baroni et al. PRC93 (2016)015501 *

also derived by Park+Min+Rho NPA596(1996)515, Kölling+Epelbaum+Krebs+Meissner PRC80(2009)045502 & PRC84(2011)054008

Electromagnetic LECs



d^S, d_1^V, and d_2^V could be determined by $\pi\gamma$-production data on the nucleon



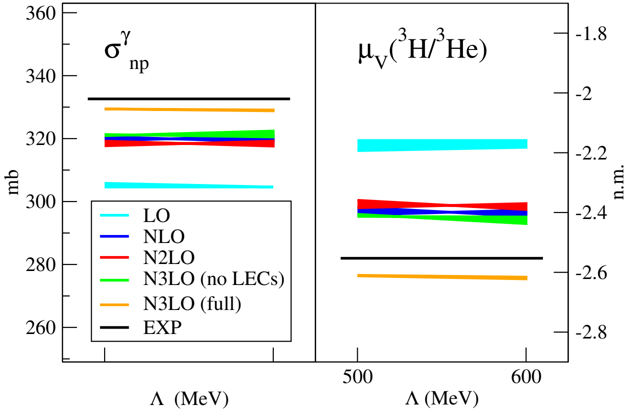
$d_2^V = 4\mu^* h_A / 9 m_N (m_\Delta - m_N)$ and
$d_1^V = 0.25 \times d_2^V$
assuming Δ-resonance saturation

Left with 3 LECs: Fixed in the $A = 2-3$ nucleons' sector

* Isoscalar sector:
  * d^S and c^S from EXPT μ_d and $\mu_S(^3\text{H}/^3\text{He})$
* Isovector sector:
  * c^V from EXPT $npd\gamma$ xsec.

    or
  * c^V from EXPT $\mu_V(^3\text{H}/^3\text{He})$ m.m.

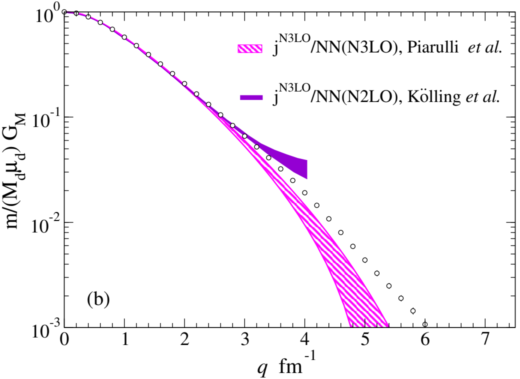
np capture x-section/ μ_V of $A = 3$ nuclei



Observable $\propto \langle \Psi_f | \mathbf{j} | \Psi_i \rangle$

Piarulli *et al.* PRC87(2013)014006

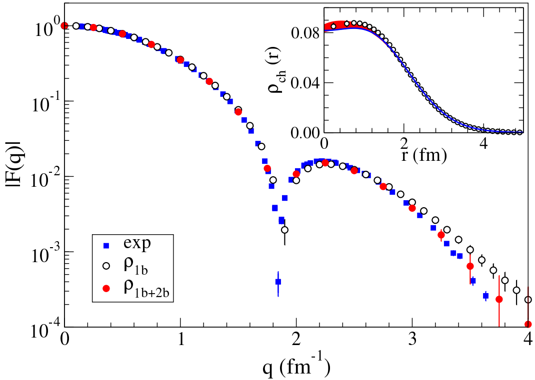
Deuteron magnetic form factor



Observable $\propto \langle \Psi_f | \mathbf{j} | \Psi_i \rangle$

PRC86(2012)047001 & PRC87(2013)014006

^{12}C Charge form factor

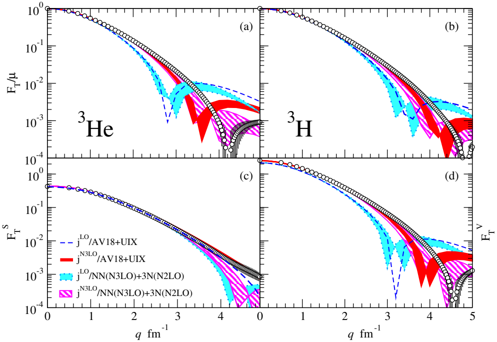


$$\propto \langle \Psi_f | \rho | \Psi_i \rangle$$

Lovato *et al.*

PRL111(2013)092501

^{3}He and ^{3}H magnetic form factors

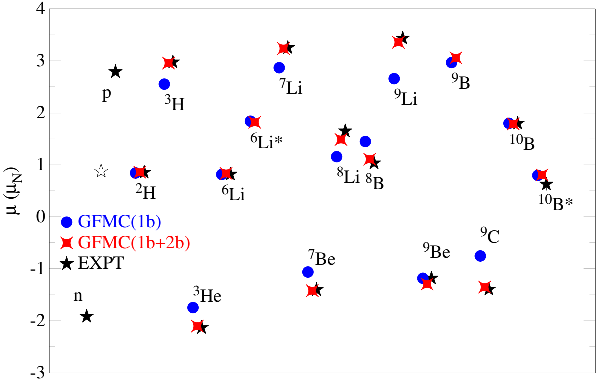


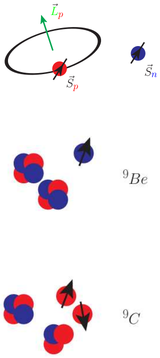
1b/1b+2b with AV18+UIX – 1b/1b+2b with χ-potentials NN(N3LO)+3N(N2LO)

$$\text{Observable} \propto \langle \Psi_f | \mathbf{j} | \Psi_i \rangle$$

Piarulli *et al.* PRC87(2013)014006

Magnetic Moments of Nuclei



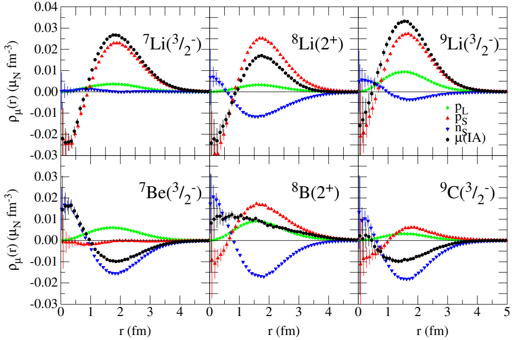


m.m.	THEO	EXP
^{9}C	-1.35(4)(7)	-1.3914(5)
^{9}Li	3.36(4)(8)	3.4391(6)

chiral truncation error based on EE *et al.* error algorithm, Epelbaum, Krebs, and Meissner EPJA51(2015)53

Pastore *et al.* PRC87(2013)035503

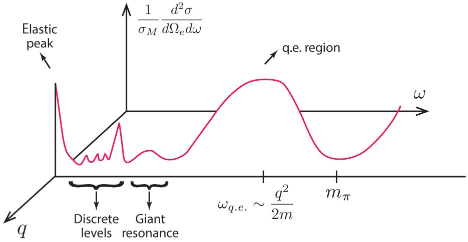
One-body magnetic densities



1b magnetic moment operator

$$\mu 1\text{b} = \mu_N \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$$

Electromagnetic Reactions

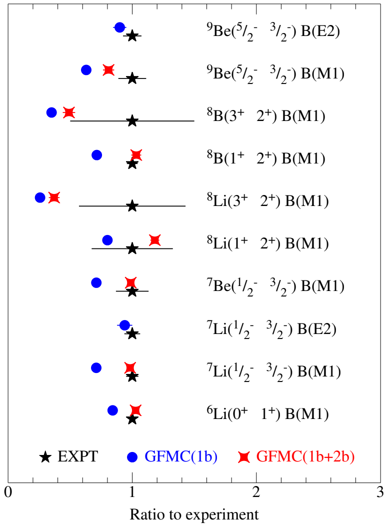


* $\omega \sim$ few MeV, $q \sim 0$: EM-decays
* $\omega \sim 10^2$ MeV: e-nucleus scattering

A coherent and accurate picture of the way electrons interact with nuclei in a wide range of energy and momenta exists, provided that two-body correlations and two-body currents are accounted for!

Electromagnetic Transitions in Light Nuclei

* 2b electromagnetic currents bring the THEORY in agreement with the EXPT
* $\sim 40\%$ 2b-current contribution found in ^{9}C m.m.
* $\sim 60 - 70\%$ of total 2b-current component is due to one-pion-exchange currents
* $\sim$ 20-30% 2b found in M1 transitions in ^{8}Be



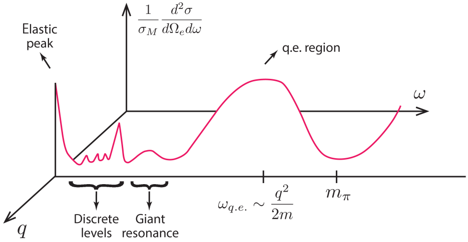
One M1 prediction: ^{9}Li$(1/2 \rightarrow 3/2)$*

\+ a number of B(E2)s

*2014 TRIUMF proposal Ricard-McCutchan *et al.*

Pastore *et al.* PRC87(2013)035503 & PRC90(2014)024321, Datar *et al.* PRL111(2013)062502

Electromagnetic Reactions



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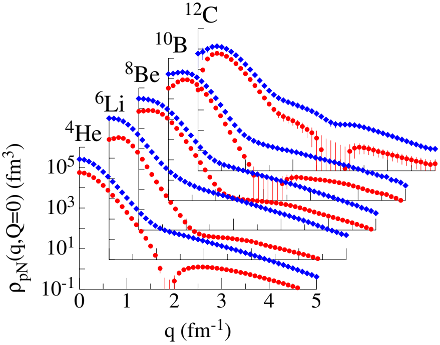
Back-to-back *np* and *pp* Momentum Distributions

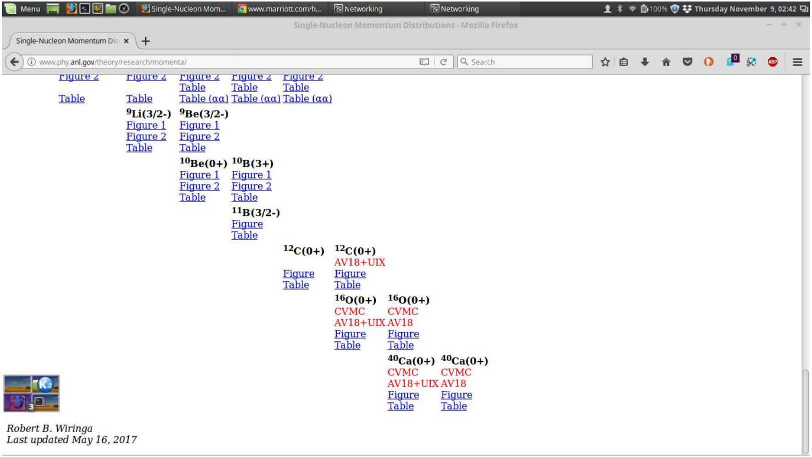


Wiringa *et al.* - PRC89(2014)024305

Nuclear properties are strongly affected by correlations!

Triple coincidence reactions $A(e,e'$ *np* or *pp*$)A-2$ measurements at JLab on ^{12}C indicate that at high values of relative momenta $(400-500$ MeV$)$, $\sim 90\%$ of the pairs are in the form of *np* pairs and $\sim 5\%$ in *pp* pairs

Two-body momentum distributions: Where to find them



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

Inclusive (e, e') scattering

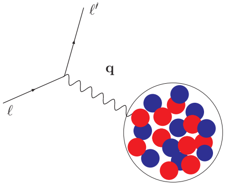
* inclusive xsecs *

$$\frac{d^2\sigma}{dE' d\Omega_{e'}} = \sigma_M \left[v_L R_L(q,\omega) + v_T R_T(q,\omega) \right]$$

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

Longitudinal response induced by $O_L = \rho$

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



* Sum Rules *

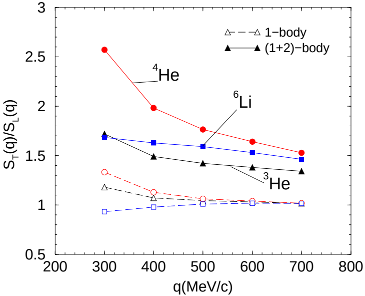
Exploit integral properties of the response functions + closure to avoid explicit calculation of the final states

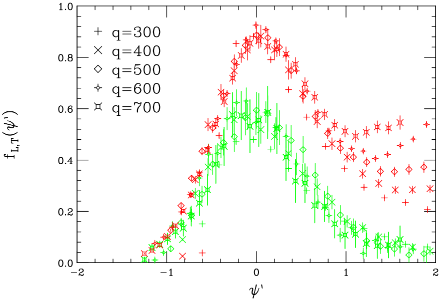
$$S(q,\tau) = \int_0^\infty d\omega\, K(\tau,\omega) R_\alpha(q,\omega)$$

* Coulomb Sum Rules *

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

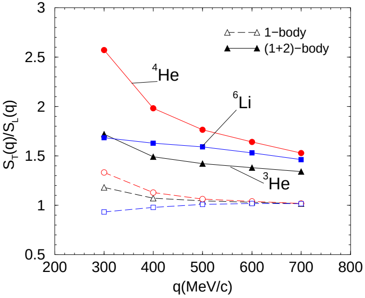
Sum Rules and the role of two-body currents





Carlson, Jourdan, Schiavilla, and Sick PRC65(2002)024002

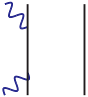
Sum Rules and Two-Body Physics



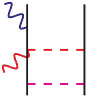
PRC65(2002)024002

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

• enhancement of the transverse response is due to interference between 1b and 2b contributions AND presence of correlations in the wave function •

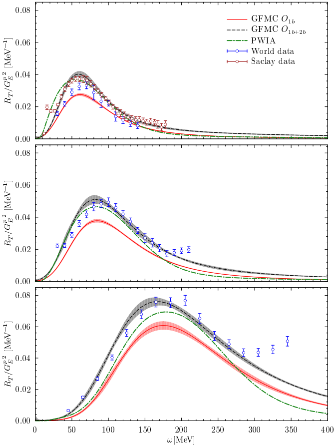


$\langle \mathbf{j}^\dagger_{1b}\ \ \mathbf{j}_{1b}\rangle\ > 0$



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

Recent Developments on ^{12}C



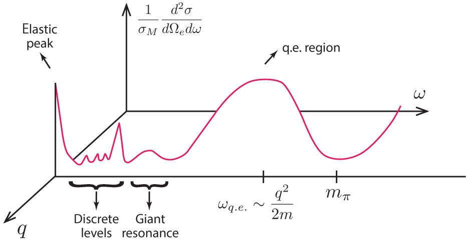
$q = [300 - 750]$ MeV

$\sim$ 100 million core hours

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

Two-body correlations and currents essential to explain the data!

Electromagnetic Reactions



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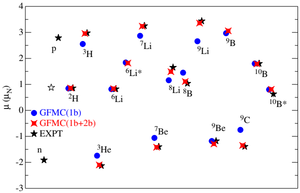
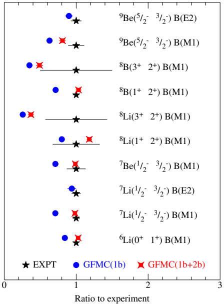
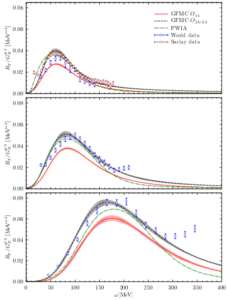
A coherent and accurate picture of the way electrons interact with nuclei in a wide range of energy and momenta exists, provided that two-body correlations and two-body currents are accounted for!

EM Moments, EM Decays and *e*-scattering off nuclei







Electromagnetic data are explained when
two-body correlations and currents are accounted for!

Pastore *et al.* PRC87(2013)035503 - Lovato *et al.* PRC91(2015)062501

Two-body Currents: Summary

* Two-body correlations and currents are essential to explain the data

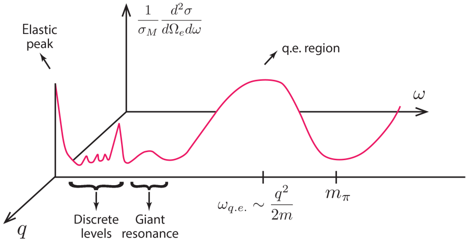
* Two-body currents provide up to $\sim 40\%$ contributions to the magnetic moments of nuclei (ground state observable)

* Two-body currents enhance the transverse response up $\sim 50\%$ (dynamical observable)

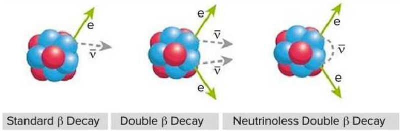
* One-pion-exchange currents provide $\sim 0.8\,\mathbf{j}_{ij}$

Neutrinos and Nuclei

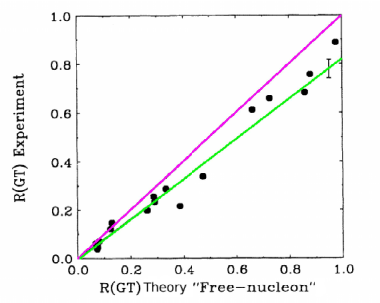
Towards a coherent and unified picture of neutrino-nucleus interactions



* $\omega \sim$ few MeV, $q \sim 0$: β-decay, $\beta\beta$-decays
* $\omega \lesssim$ tens MeV: Nuclear Rates for Astrophysics
* $\omega \sim 10^2$ MeV: Accelerator neutrinos, ν-nucleus scattering



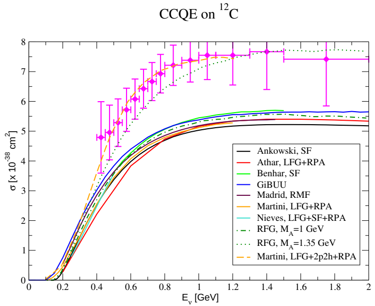
Beta Decay Rate



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

Chou *et al.* PRC47(1993)163

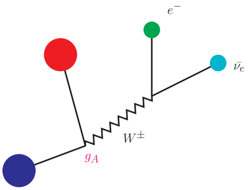
Neutrino-Nucleus Scattering



Alvarez-Ruso arXiv:1012.3871

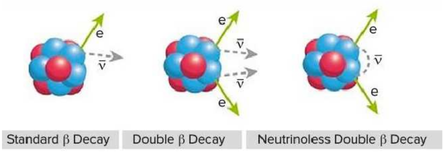
Standard Beta Decay

The "g_A problem"
and
the role of two-body correlations and two-body currents



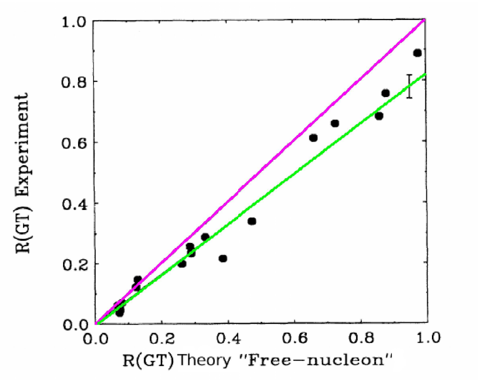
* Matrix Element $\langle \Psi_f | \mathrm{GT} | \Psi_i \rangle \propto g_A$ and Decay Rates $\propto g_A^2$ *

$$(Z, N) \rightarrow (Z+1, N-1) + e + \bar{\nu}_e$$



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

Gamow-Teller Matrix Elements Theory vs Expt



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

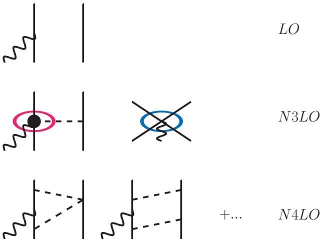
Chou *et al.* PRC47(1993)163

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

Nuclear Interactions and Axial Currents

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

so far results are available with AV18+IL7 ($A \leq 10$)
and SNPA or chiral currents (*a.k.a.* hybrid calculations)



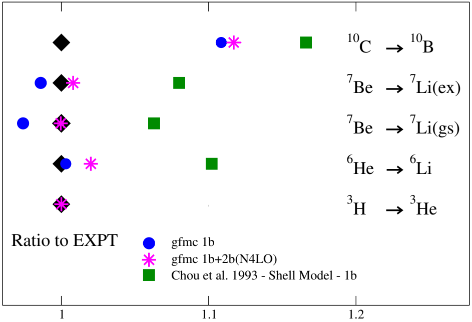
A. Baroni *et al.* PRC93(2016)015501

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 Baroni *et al.* PRC94(2016)024003
- * cutoffs $\Lambda = 500$ and 600 MeV
- * include also N4LO 3b currents (tiny)

* derived by Park *et al.* in the ′90
used (mainly at tree-level) in many calculations
* pion-pole at tree-level derived
by Klos, Hoferichter *et al.* PLB(2015)B746

Single Beta Decay Matrix Elements in $A = 6$–10



gfmc (1b) and gfmc (1b+2b); shell model (1b)

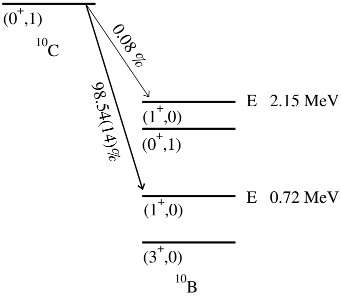
Pastore *et al.* PRC97(2018)022501

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

Based on $g_A \sim 1.27$ no quenching factor

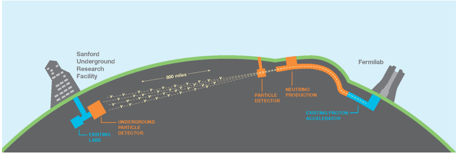
$*$ data from TUNL, Suzuki *et al.* PRC67(2003)044302, Chou *et al.* PRC47(1993)163

^{10}B

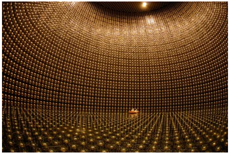


* In ^{10}B, ΔE with same quantum numbers ~ 1.5 MeV
* In $A = 7$, ΔE with same quantum numbers $\gtrsim 10$ MeV

Nuclei for Accelerator Neutrinos' Experiments

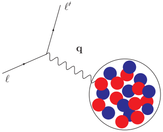


LBNF



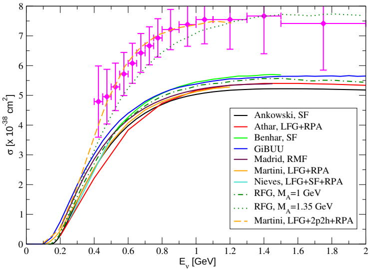
T2K

Neutrino-Nucleus scattering



$$P(\nu_\mu \to \nu_e) = sin^2 2\theta sin^2 \left(\frac{\Delta m^2_{21} L}{2E_\nu}\right)$$

CCQE on ^{12}C

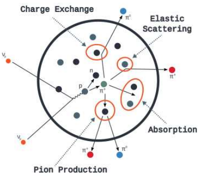


Alvarez-Ruso arXiv:1012.3871

* Nuclei of ^{12}C, ^{40}Ar, ^{16}O, ^{56}Fe, ... *

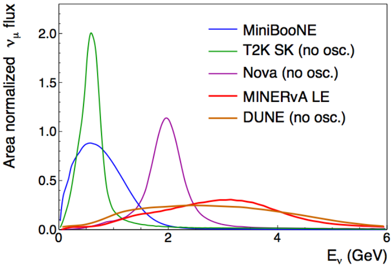
are the DUNE, MiniBoone, T2K, Minerνa ... detectors' active material

Nuclei for Accelerator Neutrinos' Experiments: More in Detail



Tomasz Golan

Neutrino Flux

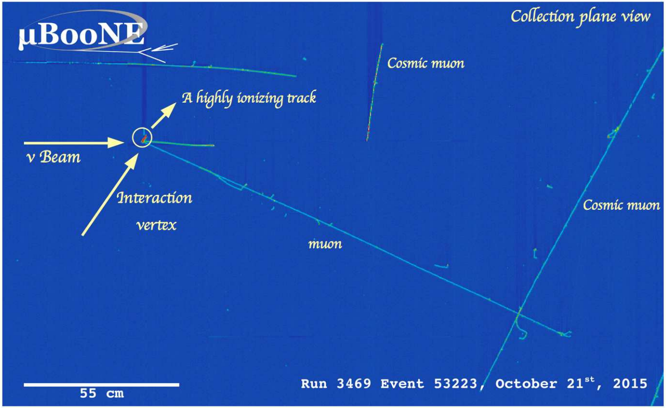


Phil Rodrigues

* Oscillation Probabilities depend on the initial neutrino energy E_ν
* Neutrinos are produced via decay-processes, E_ν is unknown!

$$P(\nu_\mu \to \nu_e) = sin^2 2\theta sin^2 \left(\frac{\Delta m^2_{21} L}{2E_\nu} \right)$$

* E_ν is reconstructed from the final state observed in the detector
* !! Accurate theoretical neutrino-nucleus cross sections are vital !! to E_ν reconstruction


μBooNE
Collection plane view
Cosmic muon
A highly ionizing track
ν Beam
Interaction
vertex
muon
Cosmic muon
55 cm
Run 3469 Event 53223, October 21st, 2015

μBoone

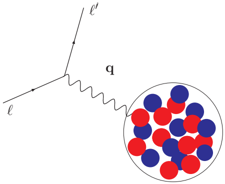
Inclusive $(e,\nu$ scattering

* inclusive xsecs *

$$\frac{d^2\sigma}{dE' d\Omega_{e'}} = \sigma_M \left[v_L R_L(q,\omega) + v_T R_T(q,\omega) \right]$$

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

Longitudinal response induced by $O_L = \rho$
Transverse response induced by $O_T = \mathbf{j}$
... 5 nuclear responses in ν-scattering...



* Sum Rules *

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

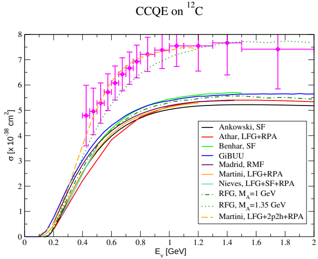
$$S(q,\tau) = \int_0^\infty d\omega\, K(\tau,\omega) R_\alpha(q,\omega)$$

* Coulomb Sum Rules *

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

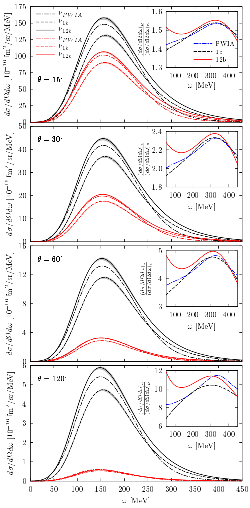
Recent Developments on ^{12}C: Inclusive QE Scattering

Charge-Current Cross Section



Alvarez-Ruso arXiv:1012.3871

NC Inclusive Xsec



$q = 750$ MeV

Lovato & Gandolfi *et al.* PRC97(2018)022502

$\sim$ 100 million core hours

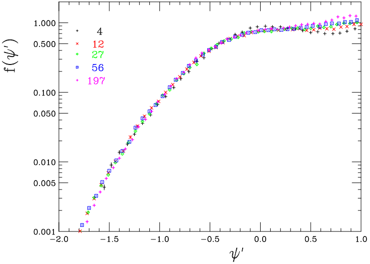
CHALLENGES:

1. How do we describe electroweak-scattering off $A > 12$ without loosing two-body physics (correlations and two-body currents)?
2. How to incorporate (more) exlusive processes?

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

Factorization: Short-Time Approximation

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

$$R_\alpha(q,\omega) = \int dt \langle\, 0|O_\alpha^\dagger(\mathbf{q})\, e^{i(H-\omega)t}\, O_\alpha(\mathbf{q})|0\,\rangle$$

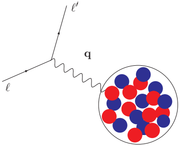
At short time, expand $P(t) = e^{i(H-\omega)t}$ and keep up to 2b-terms

$$H \sim \sum_i t_i + \sum_{i<j} v_{ij}$$

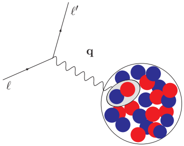
and

$$O_i^\dagger P(t) O_i + O_i^\dagger P(t) O_j + O_i^\dagger P(t) O_{ij} + O_{ij}^\dagger P(t) O_{ij}$$

1b

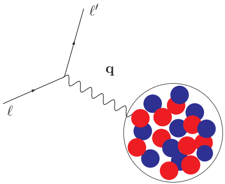


2b



WITH
Carlson & Gandolfi (LANL) & Schiavilla (ODU+JLab) & Wiringa (ANL)

Factorization up to one body - The Plane Wave Impulse Approximation



In PWIA:

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

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

$$O_\alpha(\mathbf{q}) = O_\alpha^{(1)}(\mathbf{q}) = \text{1b}$$

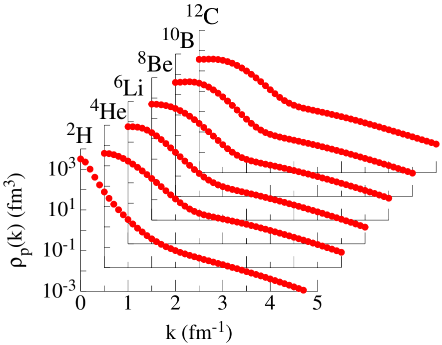
$$|f\rangle \sim e^{i(\mathbf{k}+\mathbf{q})\cdot\mathbf{r}} = \text{free single nucleon w.f.}$$

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

$$R_L^{\text{PWIA}}(q,\omega) = \int d\mathbf{k}\, n_p(\mathbf{k}) \delta\left(\omega - \frac{(\mathbf{k}+\mathbf{q})^2}{2m_N} + \frac{\mathbf{k}^2}{2m_N}\right)$$

$$O_L^{(1)}(\mathbf{q}) = e \sum_{i=1}^{A} \frac{1+\tau_{i,z}}{2} e^{i\mathbf{q}\cdot\mathbf{r}_i}$$

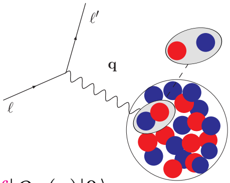
Proton Momentum Distributions



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/

Factorization up to two-body operators: 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

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

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

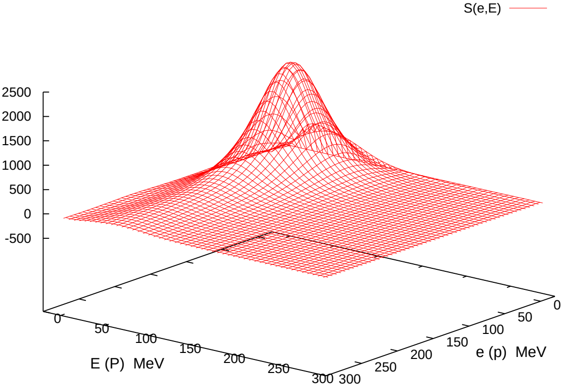
$$|f\rangle \quad \sim \quad |\psi_{p,P,J,M,L,S,T,M_T}(r,R)\rangle = \text{correlated two} - \text{nucleon w.f.}$$

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

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

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

The Short-Time Approximation



Transverse “response-density” 1b + 2b for ^4He

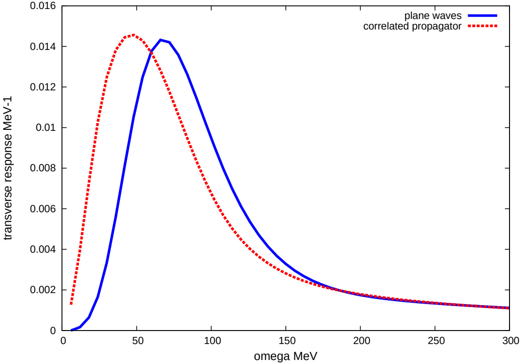
$$R_\alpha(q,\omega) \qquad \sim \int \delta\left(\omega + E_0 - E_f\right) d\Omega_P \, d\Omega_p \, dP \, dp \left[p^2 \, P^2 \langle\, 0 | O_\alpha^\dagger(\mathbf{q}) | \mathbf{p}, \mathbf{P} \rangle \langle\, \mathbf{p}, \mathbf{P} | O_\alpha(\mathbf{q}) | 0 \rangle \right]$$

* Preliminary results *

STA Transverse Response

$q = 300$ MeV

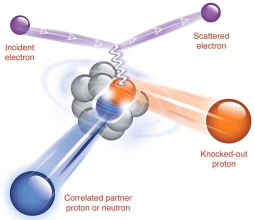
Plane Wave Propagator vs Correlated Propagator

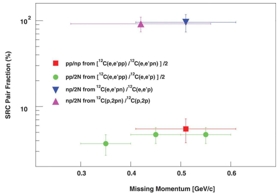


$$R_\alpha(q,\omega) \sim \int \delta\left(\omega + E_0 - E_f\right) d\Omega_P\, d\Omega_p\, dP\, dp\, \left[p^2\, P^2 \langle\, 0|O^\dagger_\alpha(\mathbf{q})|\mathbf{p},\mathbf{P}\rangle\langle\, \mathbf{p},\mathbf{P}|O_\alpha(\mathbf{q})|0\rangle\right]$$

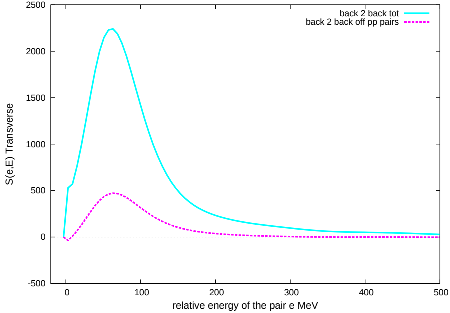
* Preliminary results *

STA back to back scattering



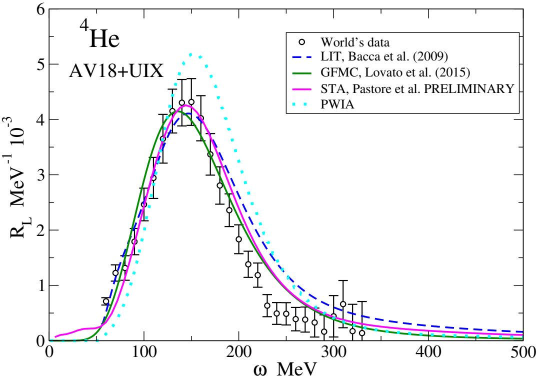


JLab, Subedi *et al.* Science320(2008)1475



$q = 500$ MeV, $E = 69$ MeV pp vs tot

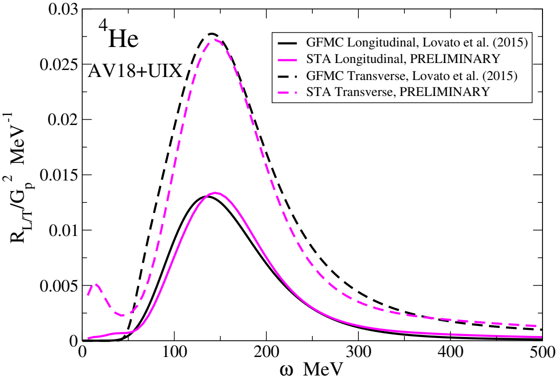
* Preliminary results *



Longitudinal Response function at $q = 500$ MeV

* Preliminary results *

The Short-Time Approximation



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

* Preliminary results *

Currents and Correlations: Summary

Two-nucleon correlations and two-body electroweak currents
are crucial to explain available experimental data of both static (ground state properties) and dynamical (cross sections and rates) nuclear observables

* Two-body currents can give $\sim 30-40\%$ contributions and improve on theory/EXPT agreement

* Calculations of $\beta-$ and ($\beta\beta-$decay) m.e.'s in $A \leq 12$ indicate two-body physics (currents and correlations) is required

* Short-Time-Approximation to evaluate ν-A scattering in $A > 12$ nuclei is in excellent agreement with exact calculations and data

* We are developing a coherent picture for neutrino-nucleus interactions *