Few-Body Physics with Relation to Neutrinos

Saori Pastore
HUGS Summer School
Jefferson Lab - Newport News VA, June 2018

Thanks to the Organizers

Neutrinos (Fundamental Symmetries) and Nuclei

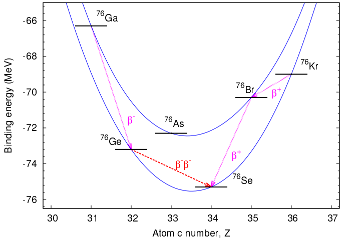
Topics (5 hours)

* Nuclear Theory for the Neutrino Experimental Program ✓
* Microscopic (or *ab initio*) Description of Nuclei ✓
* "Realistic" Models of Two- and Three-Nucleon Interactions ✓
* "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 ✓

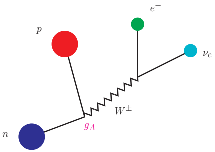
Correlations and Currents in Neutrinoless Double Beta Decay

Jefferson Lab

Standard Single and Double Beta Decays



J. Menéndez - arXiv:1703.08921v1

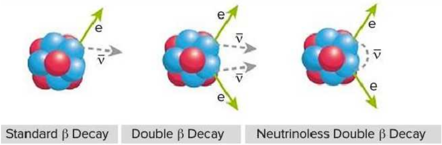


Maria Geoppert-Mayer

$$\text{single beta decay: } (Z,N) \to (Z+1,N-1) + e + \bar{\nu}_e$$

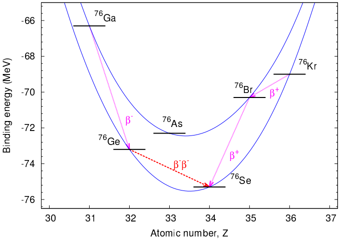
$$\text{double beta decay: } (Z,N) \to (Z+2,N-2) + 2e + 2\bar{\nu}_e$$

$$\text{lepton \# } L = l - \bar{l} \text{ is conserved}$$

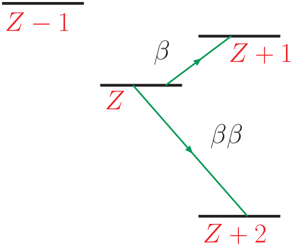


2015 Long Range Plane for Nuclear Physics

Double Beta Decay



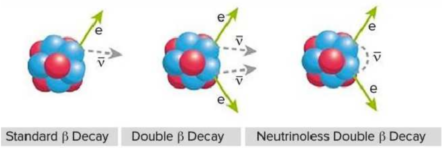
J. Menéndez - arXiv:1703.08921v1



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

double beta decay: $(Z,N) \rightarrow (Z+2,N-2) + 2e + 2\bar{\nu}_e$

lepton # $L = l - \bar{l}$ is conserved

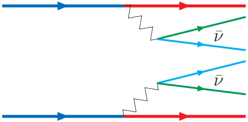


2015 Long Range Plane for Nuclear Physics

Majorana Neutrino

Maria Geoppert-Mayer

$\nu \neq \bar{\nu}$

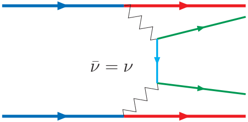


$(Z, N) \to (Z+2, N-2) + 2e + 2\bar{\nu}_e$

lepton # $L = l - \bar{l}$ is conserved

Ettore Majorana

$\nu = \bar{\nu}$



$(Z, N) \to (Z+2, N-2) + 2e$

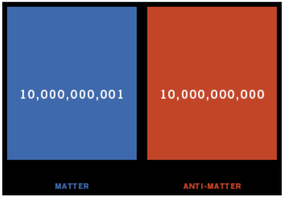
lepton # $L = l - \bar{l}$ is not conserved

$\beta\beta$ and $0\nu\beta\beta$ decays kinematics are different

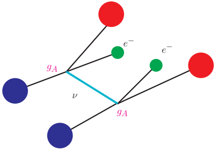
$\omega \sim$ few MeV in both processes

$\mathbf{q} \sim 0$ in $\beta\beta$-decay and $\mathbf{q} \sim$ hundreds of MeVs in $0\nu\beta\beta$-decay

Neutrinoless Double Beta Decay



H. Murayama

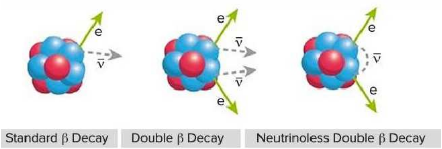


Ettore Majorana

$0\nu\beta\beta$ neutrinoless double beta decay

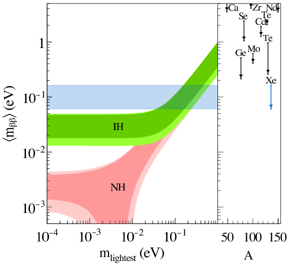
$$(Z,N) \to (Z+2, N-2) + 2e$$

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

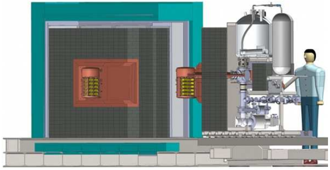


2015 Long Range Plane for Nuclear Physics

Nuclear Physics for Neutrinoless Double Beta Decay Searches

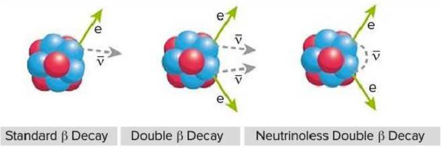


J. Engel and J. Menéndez - arXiv:1610.06548



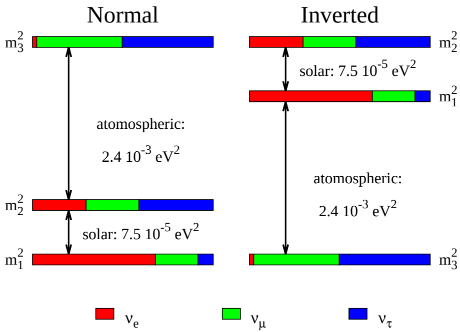
Majorana Demonstrator

$0\nu\beta\beta$-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) ~ 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

Neutrinos' Mass Hierarchy



JUNO coll. - J.Phys.G**43**(2016)030401

$$m_{\beta\beta} = f(m_1, m_2, m_3)$$

We will number (just for convenience) the massive neutrinos in such a way that $m_1 < m_2$, so that $\Delta m^2_{21} > 0$. cit. PDG2017

Neutrinoless Double Beta Decay Candidates

Half Life and Nuclear Matrix Element

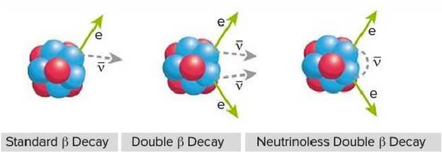
$$\frac{1}{\tau_{1/2}} \propto |M^{0\nu}|^2 \times m_{\beta\beta}{}^2$$

$M^{0\nu} = 0\nu\beta\beta$ nuclear matrix element

$m_{\beta\beta} = f(m_1, m_2, m_3)$

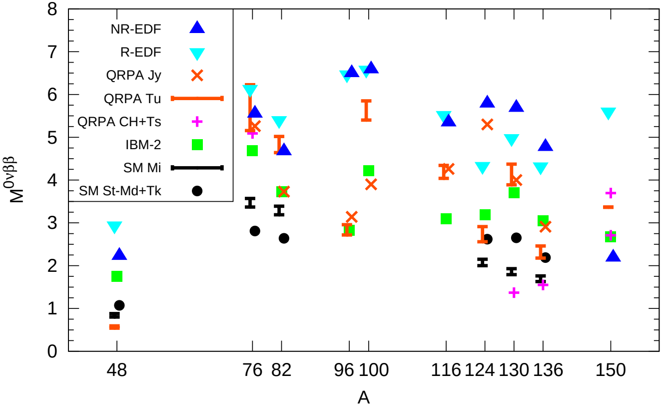
Candidates (smallest nucleus $A = 48$)

^{48}Ca ^{76}Ge ^{82}Se ^{96}Zr ^{100}Mo ^{116}Cd ^{128}Te ^{130}Te ^{136}Xe ^{150}Nd



2015 Long Range Plane for Nuclear Physics

Neutrinoless Double Beta Decay Matrix Elements: Status

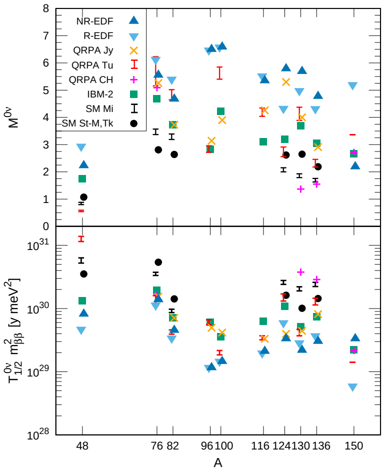


J. Engel and J. Menéndez - arXiv:1610.06548

^{48}Ca ^{76}Ge ^{82}Se ^{96}Zr ^{100}Mo ^{116}Cd ^{128}Te ^{130}Te ^{136}Xe ^{150}Nd

calculated $M^{0\nu}$ can differ by a factor of 3

Neutrinoless Double Beta Decay Half Life: Status



J. Engel and J. Menéndez - arXiv:1610.06548

$$\tau_{1/2} \times m_{\beta\beta}{}^2 = |M^{0\nu}|^{-2}$$

Quantum Monte Carlo calculations of $0\nu\beta\beta$-decay matrix elements

* Quantum Monte Carlo (QMC) Methods solve the many-nuclear problem exactly

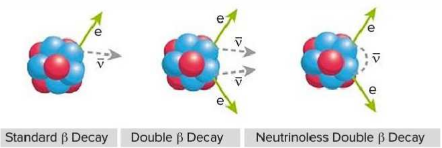
* QMC (currently) computationally limited to $A \leq 12$ nuclei

* QMC method, many-body Hamiltonians and electroweak currents largely and successfully tested against available experimental data

* Calculate $0\nu\beta\beta$-decay matrix elements in light nuclei within the above framework

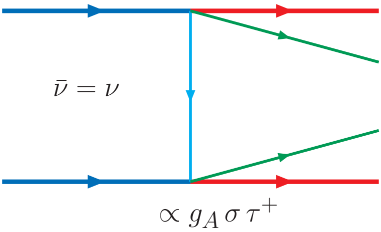
* Not directly relevant to the experimental program ($0\nu\beta\beta$-decay not occurring in $A \leq 12$ nuclei)

* Very important from the theoretical stand point of view to
  i) benchmark different computational methods
  ii) identify most relevant contributions to the matrix elements
  iii) have an insight into the dynamics of the process



2015 Long Range Plane for Nuclear Physics

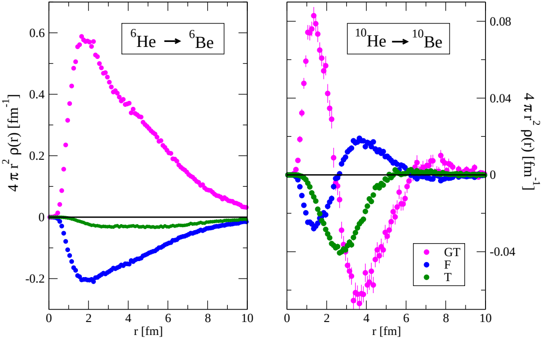
$0\nu\beta\beta$-decay mediated by a neutrino



$$v_{0\nu} = \sum_i h_i(r)\, O_{12} \qquad O_{12} = [1, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2, S_{12}] \otimes \tau_1^+ \, \tau_2^+$$

F, GT, T = Fermi, Gamow-Teller, Tensor

F, GT, and T Transition Densities



* $\Delta T = 0$

^{6}He(1)→^{6}Be(1)
^{8}He(2)→^{8}Be*(2)
^{10}Be(1)→^{10}C(1)

* $\Delta T = 2$

^{8}He(1)→^{8}Be(0)
^{10}He(3)→^{10}Be(1)
^{12}Be(2)→^{12}C(0)

$$\text{F} = \tau_{1,+}\,\tau_{2,+} \;\; ; \text{GT} = \tau_{1,+}\,\tau_{2,+}\,\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 \;\; ; \text{T} = \tau_{1,+}\,\tau_{2,+}\,S_{12}$$

arXiv:1710.05026

Lepton-number violating transition operators

$$\upsilon_\nu \sim L_\nu \, \tau_{1,+}\, \tau_{2,+} \frac{\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2}{m_\pi \, \mathbf{q}^2} + \cdots + \upsilon_\nu{}^{\mathrm{N2LO-loop}\,*}$$

$$\upsilon_{\pi\pi} \sim L_{\pi\pi} \, \tau_{1,+}\, \tau_{2,+} \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{q}\, \boldsymbol{\sigma}_2 \cdot \mathbf{q}}{m_\pi \, (\mathbf{q}^2 + m_\pi^2)^2}$$

$$\upsilon_{\pi} \sim L_{\pi} \, \tau_{1,+}\, \tau_{2,+} \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{q}\, \boldsymbol{\sigma}_2 \cdot \mathbf{q}}{m_\pi^3 \, (\mathbf{q}^2 + m_\pi^2)}$$

$$\upsilon_{\mathrm{NN}} \sim L_{\mathrm{NN}} \, \tau_{1,+}\, \tau_{2,+} \frac{\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2}{m_\pi^3}$$

$L_{\pi\pi}$, L_π, L_{NN} encode hadronic and model dependent particle physics

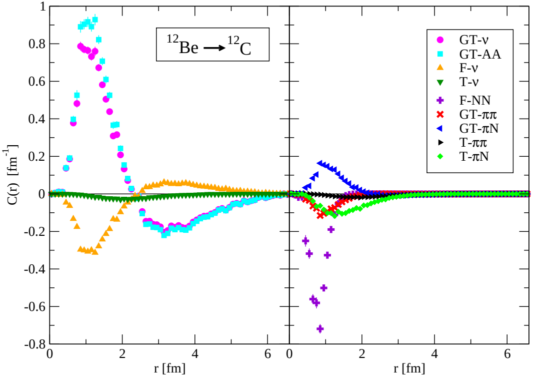
* Cirigliano & Dekens & Mereghetti & Walker-Loud in arXiv:1710.01729

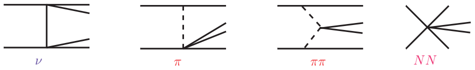
$$\upsilon_{0\nu} = \sum_i h_i(r)\, O_{12} \qquad O_{12} = [1, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2, S_{12}] \otimes \tau_1^+ \, \tau_2^+$$

with Mereghetti & Dekens & Cirigliano & Carlson & Wiringa

PRC97(2018)014606

Double beta-decay Matrix Elements in $A = 12$

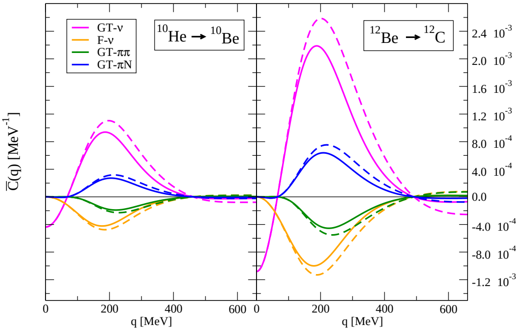




with Mereghetti & Dekens & Cirigliano & Carlson & Wiringa

PRC97(2018)014606

Momentum Dependence



- Peaks at ~ 200 MeV
- Form factors on/off $\rightarrow \sim 10\%$ variation same size as $\upsilon_\nu^{\text{N2LO-loop}}$ from Cirigliano *et al.* arXiv:1710.01729
- $A = 10$ highly suppressed w.r.t. $A = 12$
- $A = 10$ small overlap between initial diffuse w.f. ($r_n \sim 3.66$ fm) and final compact w.f. ($r_p \sim 2.32$ fm)
- $A = 12$ large overlap between initial compact w.f. ($r_n \sim 2.99$ fm) and final compact w.f. ($r_p \sim 2.48$ fm)
- $A = 12$ ‘most similar’ to experimental cases

with Mereghetti & Dekens & Cirigliano & Carlson & Wiringa PRC97(2018)014606

“Worsening” the VMC wave function

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

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

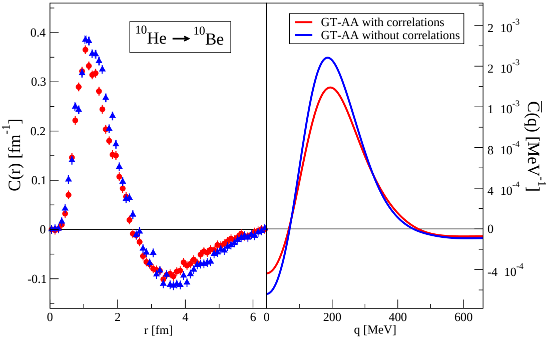
* single-particle $\Phi_A(JMTT_3)$ is fully antisymmetric and translationally invariant
* central pair correlations $f_c(r)$ keep nucleons at favorable pair separation
* pair correlation operators U_{ij} reflect influence of v_{ij} (AV18)
* triple correlation operators U_{ijk} reflect the influence of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

In an uncorrelated wave function
U_{ij} from pion-exchange and U_{ijk} are turned off

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

Wiringa, PRC43(1991)1585

Sensitivity to 'pion-exchange-like' correlations



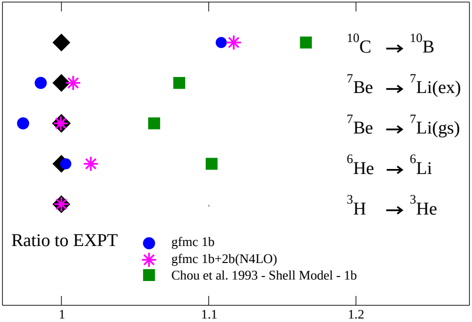
* no 'pion-exchange-like' correlation operators U_{ij}

* yes 'pion-exchange-like' correlation operators U_{ij}

* $\sim 10\%$ increase in the matrix elements corresponds

with Mereghetti & Dekens & Cirigliano & Carlson & Wiringa PRC97(2018)014606

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



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

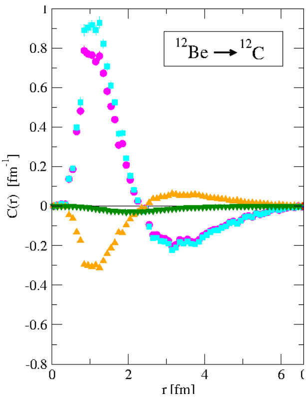
Pastore *et al.* PRC97(2018)022501

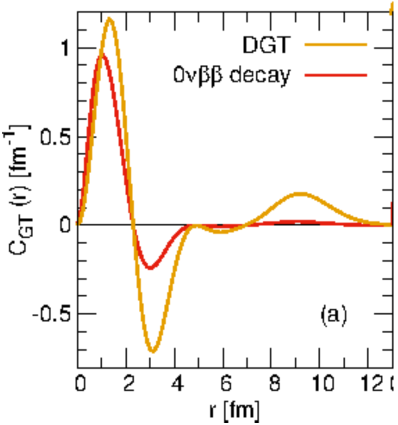
A. Baroni *et al.* PRC93(2016)015501 & PRC94(2016)024003

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

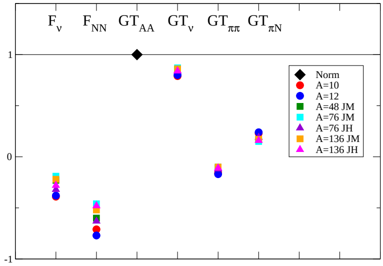
Comparison with calculations of larger nuclei

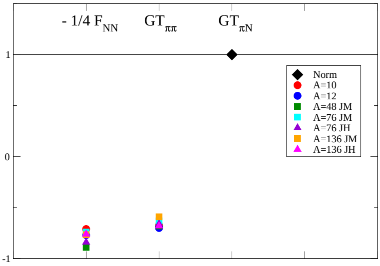




J. Menendez arXiv:1712.08691

Comparison with calculations of larger nuclei





JM = Javier Menendez private communication
JH = Hyvärien *et al.* PRC91(2015)024613

* Relative size of the matrix elements is approximately the same in all nuclei
* Short-range terms approximately the same in all nuclei

with Mereghetti & Dekens & Cirigliano & Carlson & Wiringa PRC97(2018)014606

Neutrinoless Double Beta Decay: Summary and Outlook

We studied correlations and many-body currents in single beta and neutrinoless double beta decays (NLDBD) in $A \leq 12$ nuclei

* In single beta decays the calculations based on $g_A \sim 1.27$ are in good agreement with the data and axial two-body currents provide a negligible contribution $\sim 2\%$
* In the neutrino-scattering Quasi Elastic kinematic region electroweak two-body are found to increase calculations based on one-body operators alone
* In NLDBD we tested the neutrino-exchange potentials as well as contributions of one-pion and contact- range
* Lack of correlations in the wave functions produces a $\sim 10\%$ increase in the NLDBD matrix elements

Summary and Outlook

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 *

Factorization: Short-Time Approximation

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

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

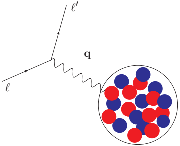
At short time, expand $P(t) = e^{i(H-\omega)t}$ and keep up to 2b-terms

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

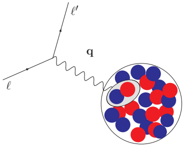
and

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

1b



2b



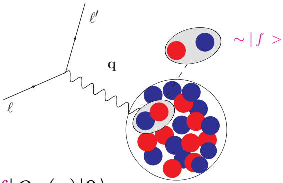
WITH

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

Factorization up to 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



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

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

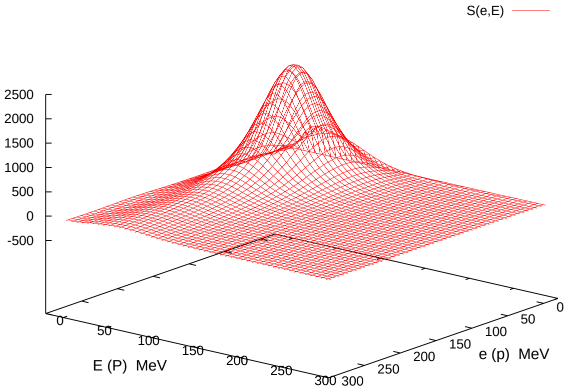
$$|f\rangle \sim |\psi_{p,P,J,M,L,S,T,M_T}(r,R)\rangle = \text{correlated two-nucleon w.f.}$$

* 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

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

The Short-Time Approximation

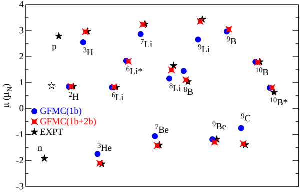


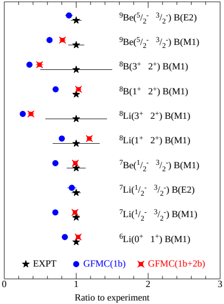
Transverse "response-density" 1b + 2b for ^4He

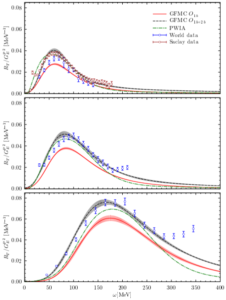
$$R_\alpha(q,\omega) \quad \sim \int \delta\,(\omega + E_0 - E_f)\, d\Omega_P\, d\Omega_p\, dP\, dp\, \left[p^2\, P^2 \langle\, 0|O^\dagger_\alpha(\mathbf{q})|\mathbf{p},\mathbf{P}\rangle\langle\,\mathbf{p},\mathbf{P}|O_\alpha(\mathbf{q})|0\rangle\right]$$

* Preliminary results *

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



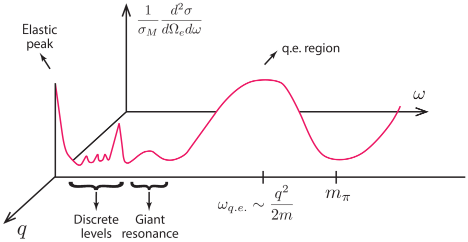




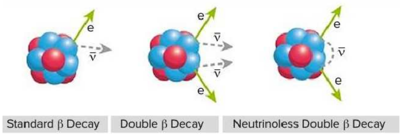
Electromagnetic data are explained when
two-body correlations and currents are accounted for!

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

Towards a coherent and unified picture of neutrino-nucleus interactions

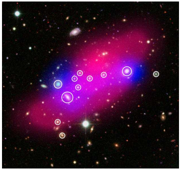


* $\omega \sim$ few MeV, $q \sim 0$: β-decay, $\beta\beta$-decays
* $\omega \lesssim$ tens MeV: Nuclear Rates for Astrophysics
* $\omega \sim 10^2$ MeV: Accelerator neutrinos, ν-nucleus scattering

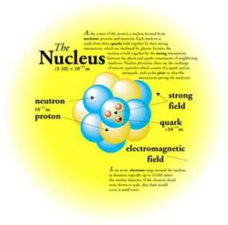


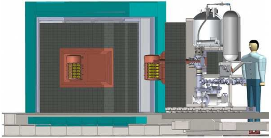
Understand Nuclei to Understand the Cosmos

Jefferson Lab

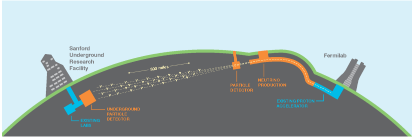


ESA, XMM-Newton, Gastaldello, CFHTL





Majorana Demonstrator

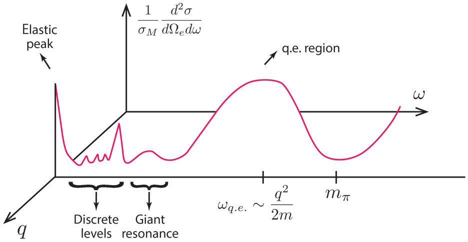


LBNF

Thank you!

saori.pastore at gmail.com

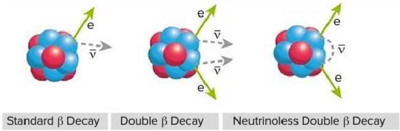
Nuclear Physics for Neutrinoless Double Beta Decay: Kinematics



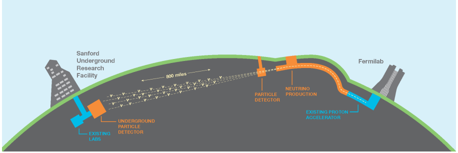
⇒ $\omega \sim$ few MeV, $q \sim 0$: EM decay, β-decay, $\beta\beta$-decays ⇐

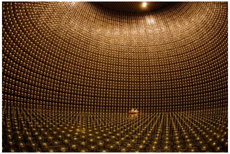
⇒ $\omega \sim$ few MeV, $q \sim$ hundreds of MeVs: $0\nu\beta\beta$-decays ⇐

* $\omega \sim 10^2$ MeV: Accelerator neutrinos, ν-nucleus scattering



Nuclei for Accelerator Neutrinos' Experiments

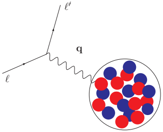




LBNF

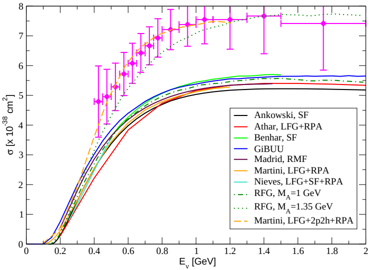
T2K

Neutrino-Nucleus scattering



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

CCQE on ^{12}C

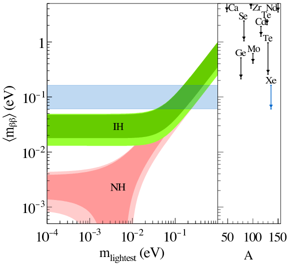


Alvarez-Ruso arXiv:1012.3871

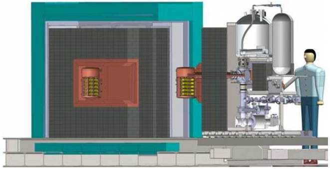
* Nuclei of ^{12}C, ^{40}Ar, ^{16}O, ^{56}Fe, ... *

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

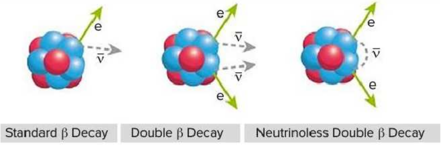


Majorana Demonstrator

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

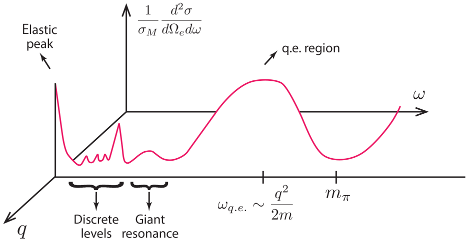
need 1 ton of material to see (if any) ~ 5 decays per year

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

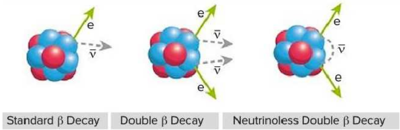


2015 Long Range Plane for Nuclear Physics

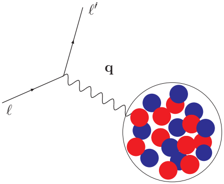
Nuclear Structure and Dynamics



* $\omega \sim$ 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, ...

$$H\Psi = E\Psi$$

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

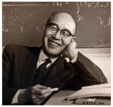
Erwin Schrödinger

Nuclear Force These Days

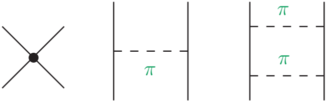
* 1930s Yukawa Potential

* 1960–1990 Highly sophisticated meson exchange potentials

* 1990s– Highly sophisticated Chiral Effective Field Theory based potentials



Hideki Yukawa



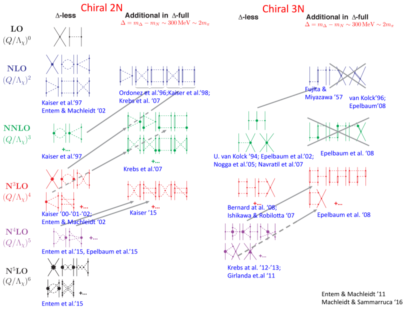
Steven Weinberg

* 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

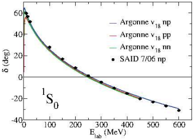
$$H = \sum_i K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

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

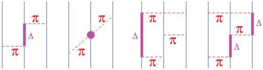
Argonne v$_{18}$: $v_{ij} = v^{\gamma}_{ij} + v^{\pi}_{ij} + v^{I}_{ij} + v^{S}_{ij} = \sum v_p(r_{ij}) O^p_{ij}$

- 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

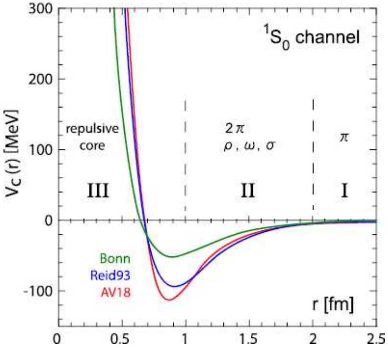
Pieper, Pandharipande, Wiringa, & Carlson, PRC **64**, 014001 (2001)
Pieper, AIP CP **1011**, 143 (2008)

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)

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

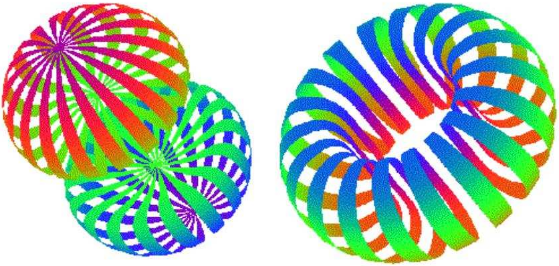
vs

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

slide from my 15 mins HUGS...

Nucleon-Nucleon Potential and the Deuteron

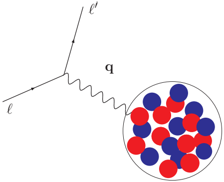
$M = \pm 1$ $M = 0$



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

$$H\Psi = E\Psi$$

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

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

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

* 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

Green's function Monte Carlo (GFMC)

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

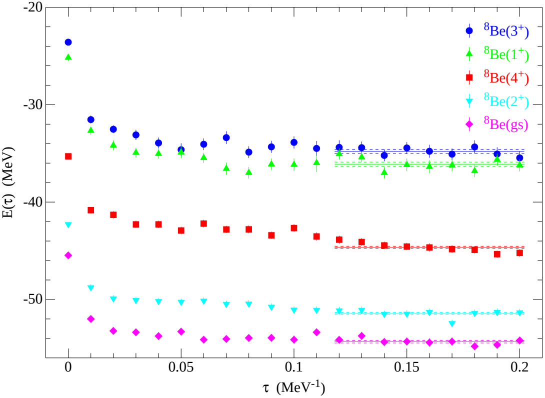
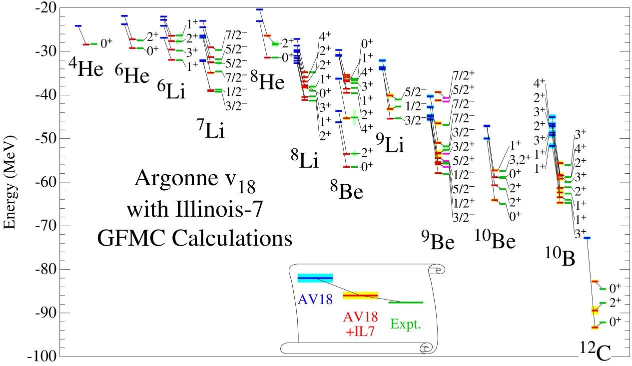


Fig. 6 (Wiringa, et al.)

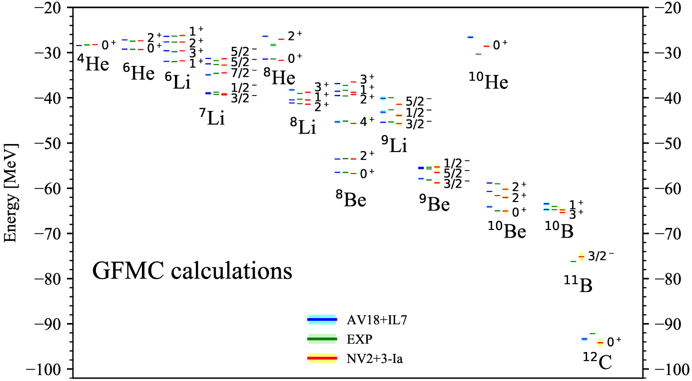
Wiringa *et al.* PRC62(2000)014001

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

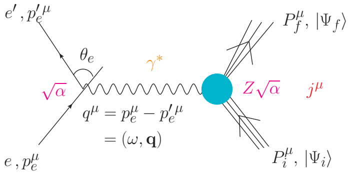
Neutrinos (Fundamental Symmetries) and Nuclei

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 ✓
* "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

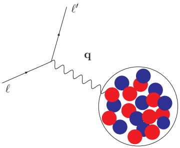
* calculated x-sections factorize into a part $\propto |\langle\Psi_f|j^{\mu}|\Psi_i\rangle|^2$ with j^{μ} nuclear EM currents and a part completely specified by the electron kinematic variables

* 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

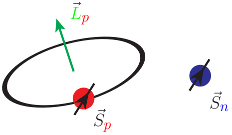
1b



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

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

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

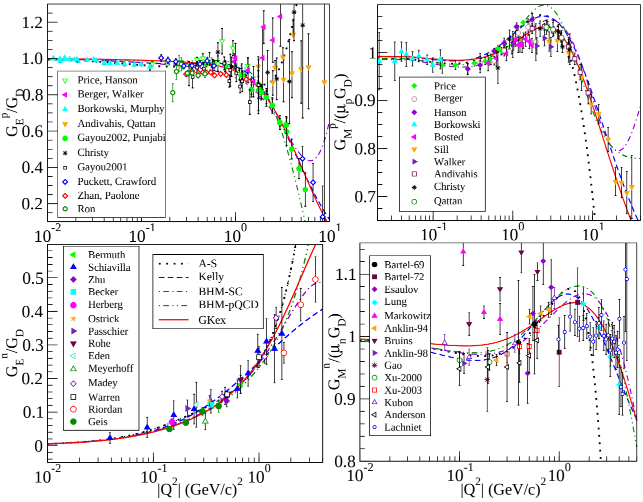


* Nucleonic electroweak form factors are taken from experimental data, and, in principle, from LQCD calculations where data are poor or scarce (*e.g.*, nucleonic axial form factor)

* 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

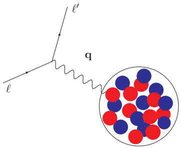
Electromagnetic Nucleonic Form Factors



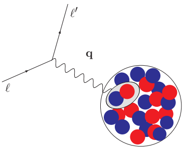
González-Jiménez Phys.Rept.524(2013)1-35

Nuclear Currents: Two-Body Component

1b



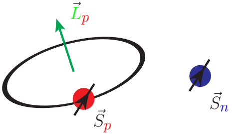
2b



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

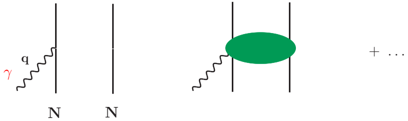
$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \dots$$

* 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

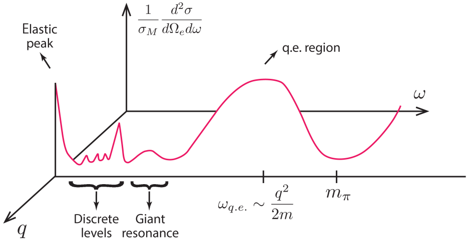
* We use MEC (SNPA) or χEFT currents



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

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

Electromagnetic Reactions



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

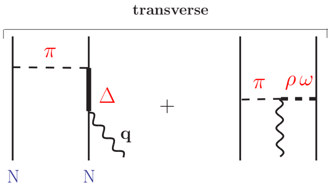
A coherent and accurate picture of the way electrons interact with nuclei in a wide range of energy and momenta exists, provided that two-body correlations and two-body currents are accounted for!

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

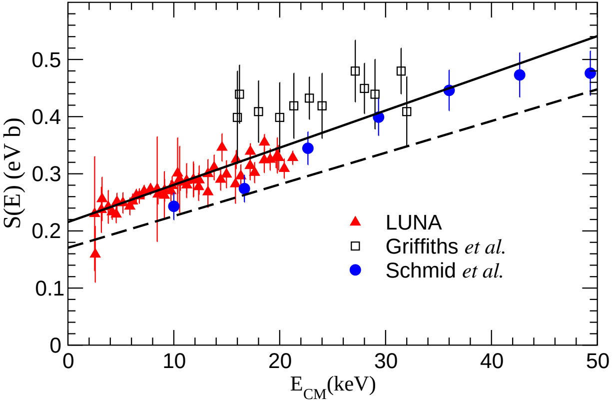
$$\mathbf{j} = \mathbf{j}^{(1)} + \mathbf{j}^{(2)}(v) + \mathbf{j}^{(3)}(V)$$



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

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

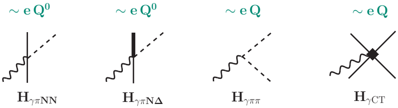
$$T_{fi} = \langle N'N' \mid H_1 \sum_{n=1}^{\infty} \left(\frac{1}{E_i - H_0 + i\eta} H_1 \right)^{n-1} \mid NN \rangle^*$$

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

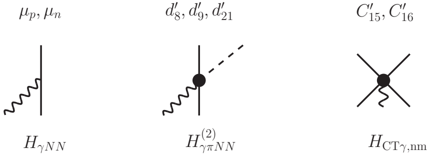
* EM H_1 obtained by minimal substitution in the π- and N-derivative couplings (same as doing $\mathbf{p} \to \mathbf{p} + e\,\mathbf{A}$, minimal coupling)

$$\begin{aligned} \nabla \pi_{\mp}(\mathbf{x}) &\to [\nabla \mp i e \mathbf{A}(\mathbf{x})]\, \pi_{\mp}(\mathbf{x}) \\ \nabla N(\mathbf{x}) &\to [\nabla - i e\, e_N \mathbf{A}(\mathbf{x})]\, N(\mathbf{x})\ , \qquad e_N = (1+\tau_z)/2 \end{aligned}$$

* 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 $F_{\mu\nu} = (\partial_\mu A_\nu - \partial_\nu A_\mu)$

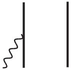
LECs are not constrained by the strong interaction
there are additional LECs fixed to EM observables

- * $H_{\gamma NN}$ 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

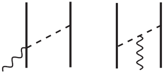
* These are the so called the "transverse" currents

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

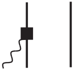
LO : $\mathbf{j}^{(-2)} \sim \mathbf{eQ^{-2}}$



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)

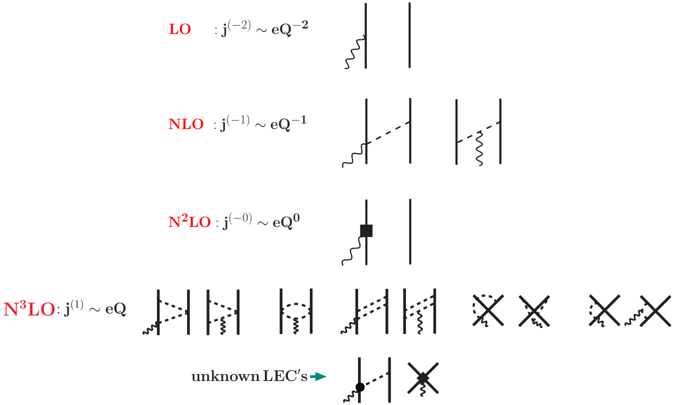
$$\upsilon_\pi(\mathbf{k}) = -\frac{g_A^2}{F_\pi^2}\frac{\boldsymbol{\sigma}_1\cdot\mathbf{k}\,\boldsymbol{\sigma}_2\cdot\mathbf{k}}{\omega_k^2}\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2$$

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

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

* LO = one-body current *

EM Currents j from Chiral Effective Field Theory



No three-body currents at this order!

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

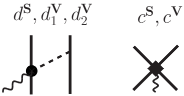
* Two-body corrections to the one-body Charge Operator appear at N3LO

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 *

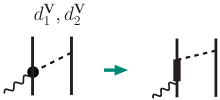
also derived by Park+Min+Rho NPA596(1996)515, Kölling+Epelbaum+Krebs+Meissner PRC80(2009)045502 & PRC84(2011)054008

Electromagnetic LECs



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

Isovector



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

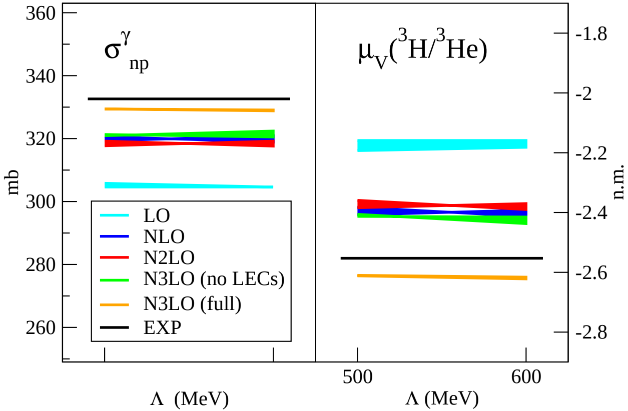
Left with 3 LECs: Fixed in the $A = 2-3$ nucleons' sector

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

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

Low-energy observables and ground state properties

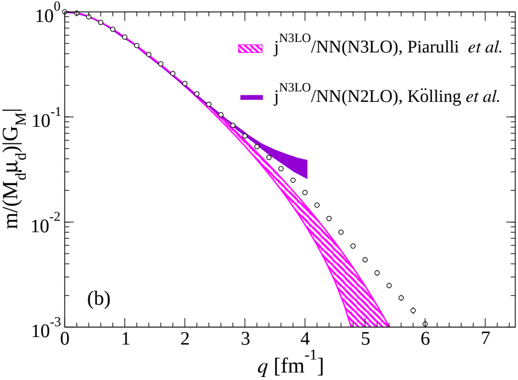
np capture x-section/ μ_V of $A = 3$ nuclei



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

Piarulli *et al.* PRC87(2013)014006

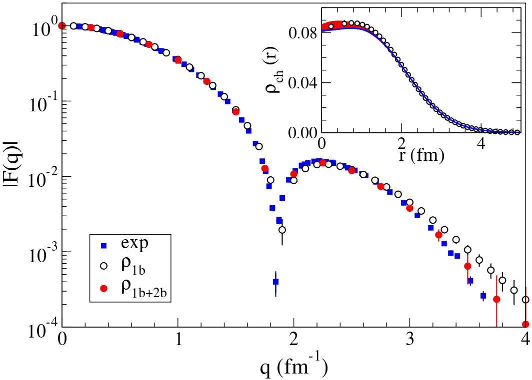
Deuteron magnetic form factor



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

PRC86(2012)047001 & PRC87(2013)014006

^{12}C Charge form factor

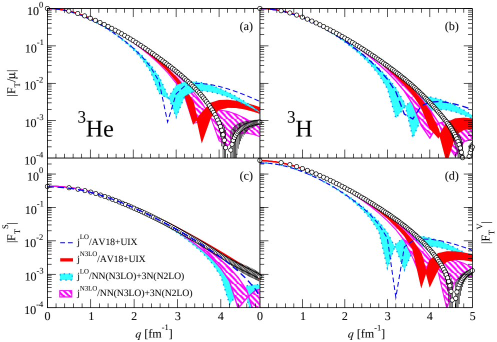


$$\propto \langle \Psi_f | \rho | \Psi_i \rangle$$

Lovato *et al.*

PRL111(2013)092501

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

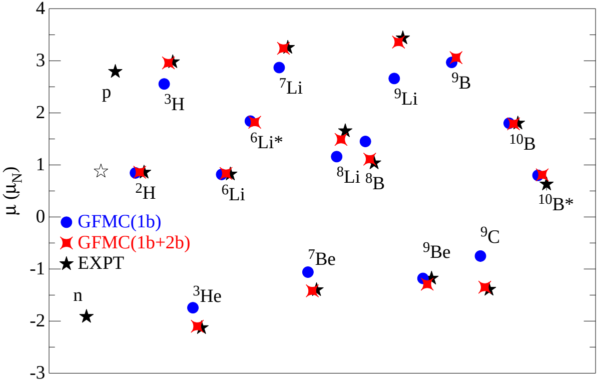


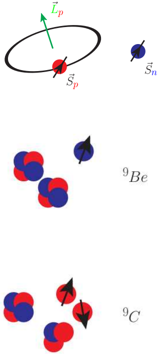
1b/1b+2b with AV18+UIX – 1b/1b+2b with χ-potentials NN(N3LO)+3N(N2LO)

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

Piarulli *et al.* PRC87(2013)014006

Magnetic Moments of Nuclei



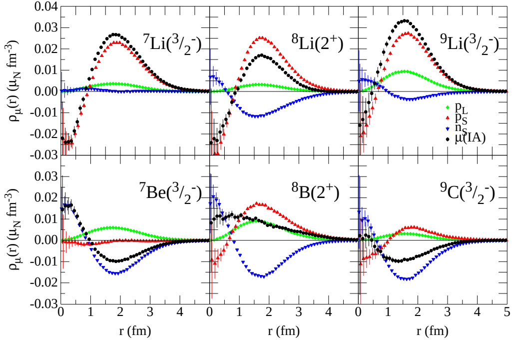


m.m.	THEO	EXP
^{9}C	-1.35(4)(7)	-1.3914(5)
^{9}Li	3.36(4)(8)	3.4391(6)

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

Pastore *et al.* PRC87(2013)035503

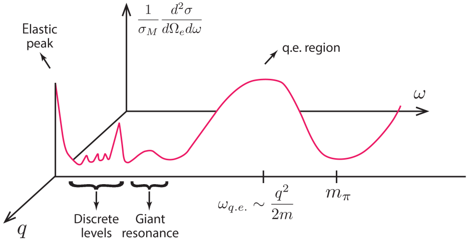
One-body magnetic densities



1b magnetic moment operator

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

Electromagnetic Reactions



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

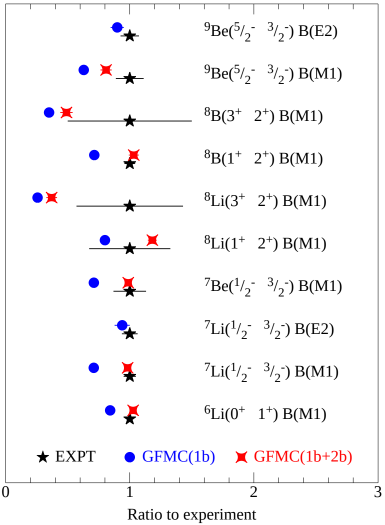
A coherent and accurate picture of the way electrons interact with nuclei in a wide range of energy and momenta exists, provided that two-body correlations and two-body currents are accounted for!

- 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$(1/2 \rightarrow 3/2)$*

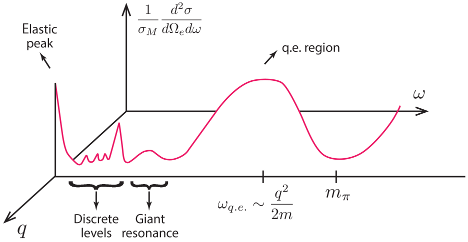
+ a number of B(E2)s

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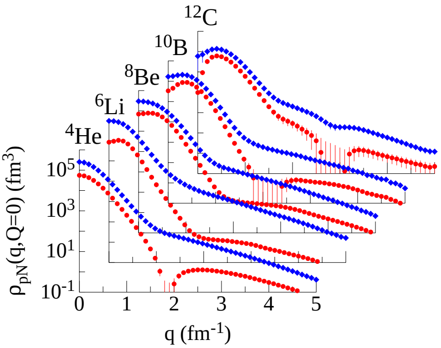
Back-to-back *np* and *pp* Momentum Distributions

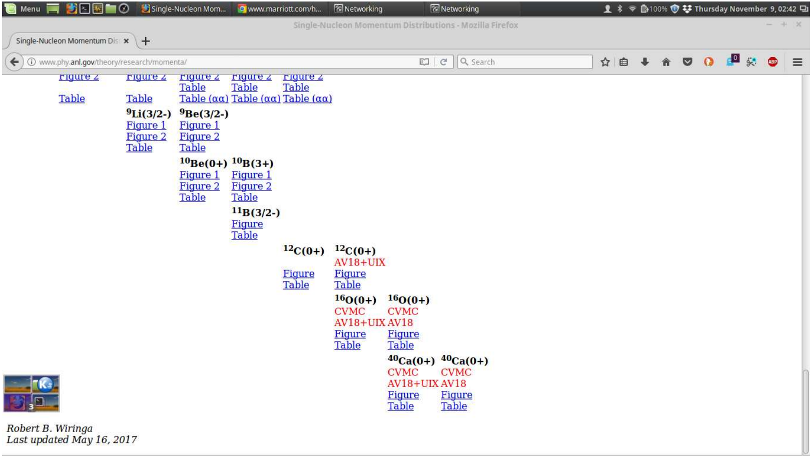


Wiringa *et al.* - PRC89(2014)024305

Nuclear properties are strongly affected by correlations!

Triple coincidence reactions $A(e,e'\ np\,\mathrm{or}\,pp)A-2$ 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/

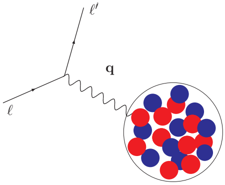
Inclusive (e,e') scattering

* 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 *

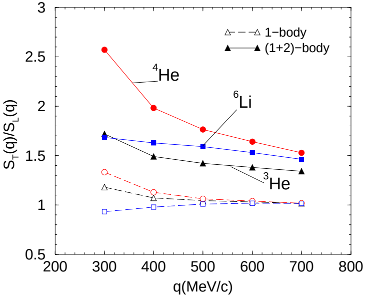
Exploit integral properties of the response functions + closure to avoid explicit calculation of the final states

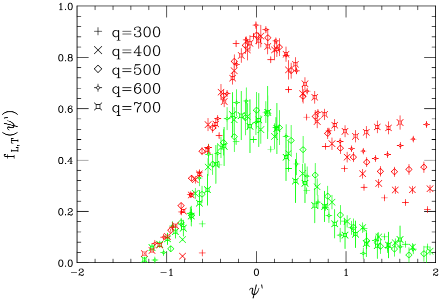
$$S(q,\tau) = \int_0^\infty d\omega\, K(\tau,\omega) R_\alpha(q,\omega)$$

* Coulomb Sum Rules *

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

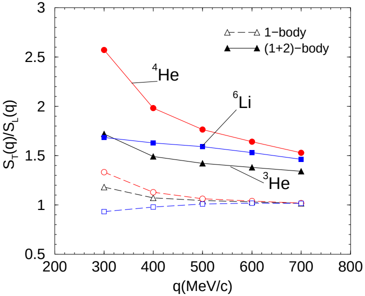
Sum Rules and the role of two-body currents





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

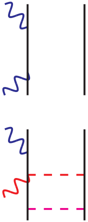
Sum Rules and Two-Body Physics



PRC65(2002)024002

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

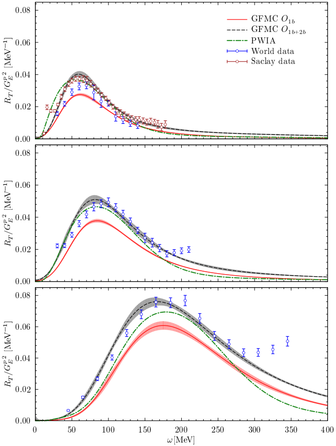
• enhancement of the transverse response is due to interference between 1b and 2b contributions AND presence of correlations in the wave function •



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

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

Recent Developments on ^{12}C



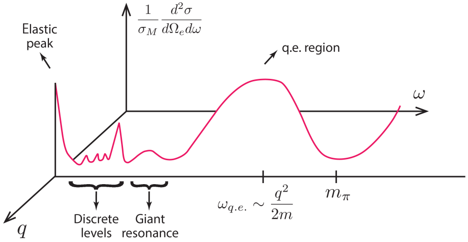
$q = [300 - 750]$ MeV

$\sim$ 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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* $\omega \sim 10^2$ MeV: e-nucleus scattering

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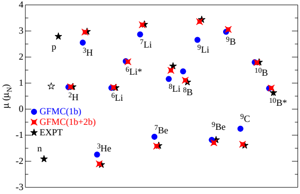
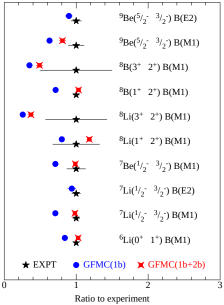
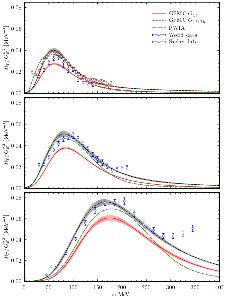
EM Moments, EM Decays and *e*-scattering off nuclei







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

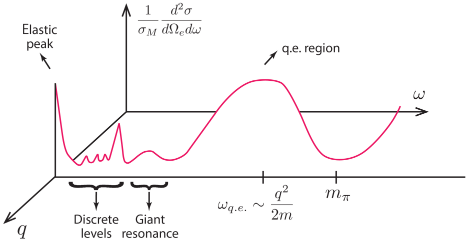
Pastore *et al.* PRC87(2013)035503 - Lovato *et al.* PRC91(2015)062501

Two-body Currents: Summary

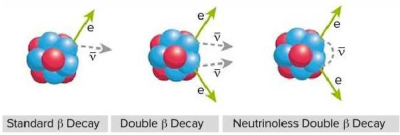
* Two-body correlations and currents are essential to explain the data
* Two-body currents provide up to $\sim 40\%$ contributions to the magnetic moments of nuclei (ground state observable)
* Two-body currents enhance the transverse response up $\sim 50\%$ (dynamical observable)
* One-pion-exchange currents provide $\sim 0.8\,\mathbf{j}_{ij}$

Neutrinos and Nuclei

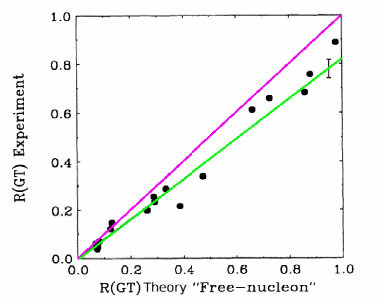
Towards a coherent and unified picture of neutrino-nucleus interactions



* $\omega \sim$ 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



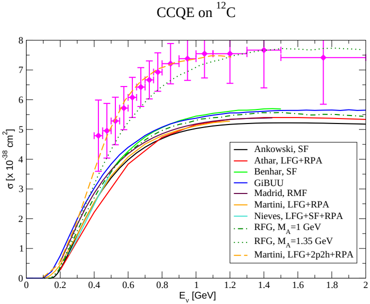
Beta Decay Rate



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

Chou *et al.* PRC47(1993)163

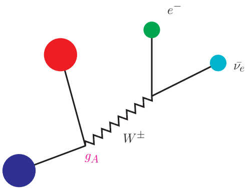
Neutrino-Nucleus Scattering



Alvarez-Ruso arXiv:1012.3871

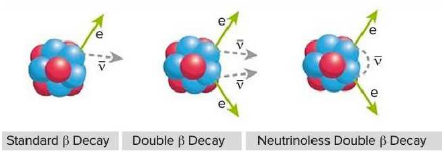
Standard Beta Decay

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



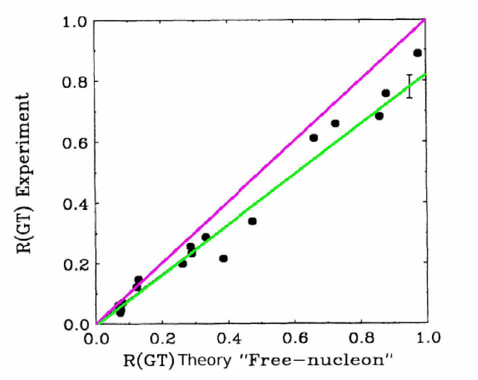
* Matrix Element $\langle \Psi_f | \mathrm{GT} | \Psi_i \rangle \propto g_A$ and Decay Rates $\propto g_A^2$ *

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



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

Gamow-Teller Matrix Elements Theory vs Expt



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

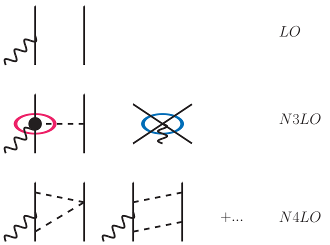
Chou *et al.* PRC47(1993)163

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

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)



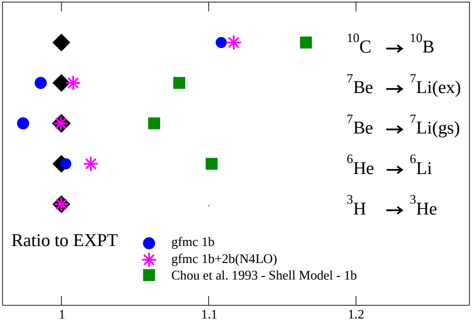
A. Baroni *et al.* PRC93(2016)015501

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)

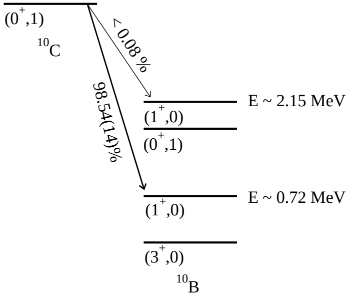
Pastore *et al.* PRC97(2018)022501

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

Based on $g_A \sim 1.27$ no quenching factor

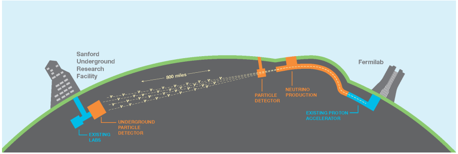
$*$ data from TUNL, Suzuki *et al.* PRC67(2003)044302, Chou *et al.* PRC47(1993)163

^{10}B

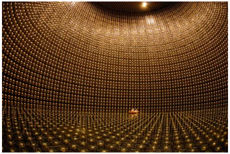


* In ^{10}B, ΔE with same quantum numbers ~ 1.5 MeV
* In $A = 7$, ΔE with same quantum numbers $\gtrsim 10$ MeV

Nuclei for Accelerator Neutrinos' Experiments

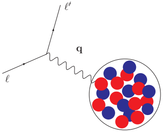


LBNF



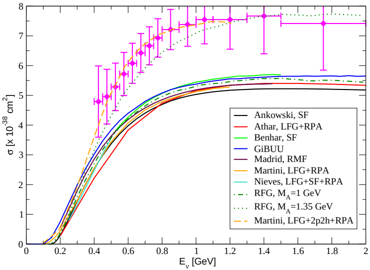
T2K

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

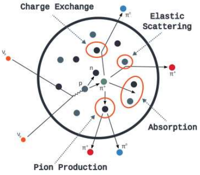


Alvarez-Ruso arXiv:1012.3871

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

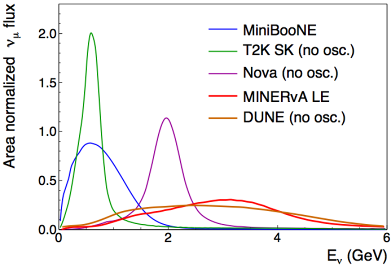
are the DUNE, MiniBoone, T2K, Minerνa ... detectors' active material

Nuclei for Accelerator Neutrinos' Experiments: More in Detail



Tomasz Golan

Neutrino Flux



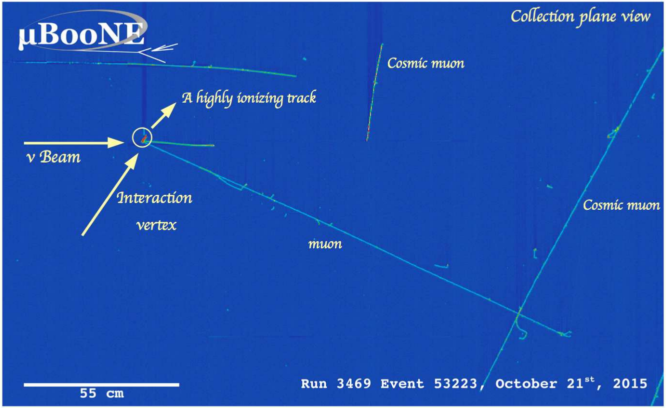
Phil Rodrigues

* 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

$e - A$ and $\nu - A$ Scattering



μBoone

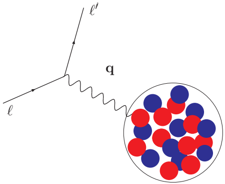
Inclusive $(e, \nu$ scattering

* 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

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

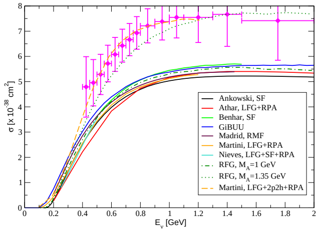
* Coulomb Sum Rules *

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

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

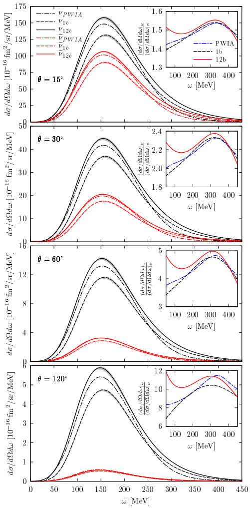
Charge-Current Cross Section

CCQE on ^{12}C



Alvarez-Ruso arXiv:1012.3871

NC Inclusive Xsec



$q = 750$ MeV

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

$\sim$ 100 million core hours

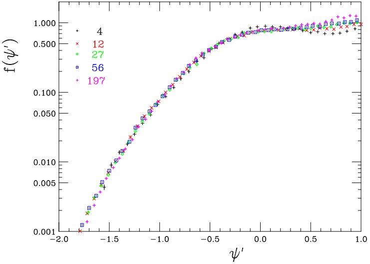
CHALLENGES:

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^{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

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

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

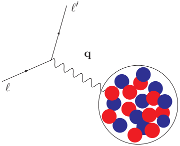
At short time, expand $P(t) = e^{i(H-\omega)t}$ and keep up to 2b-terms

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

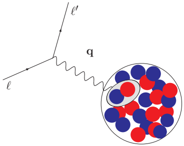
and

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

1b



2b

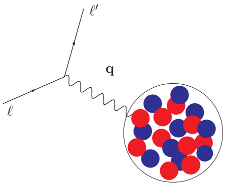


WITH
Carlson & Gandolfi (LANL) & Schiavilla (ODU+JLab) & Wiringa (ANL)

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)



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

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

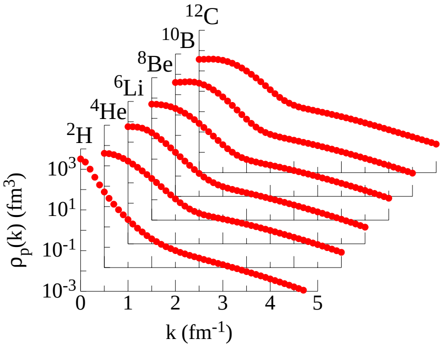
$$|f\rangle \sim e^{i(\mathbf{k}+\mathbf{q})\cdot\mathbf{r}} = \text{free single nucleon w.f.}$$

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

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

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

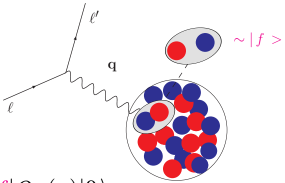
Proton Momentum Distributions



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

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

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

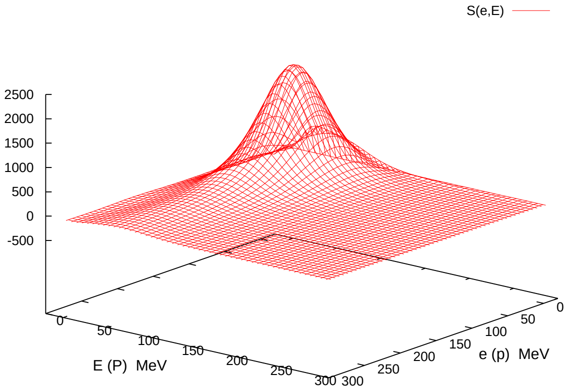
$$|f\,\rangle \sim |\psi_{p,P,J,M,L,S,T,M_T}(r,R)\rangle = \text{correlated two-nucleon w.f.}$$

* 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

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

The Short-Time Approximation



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

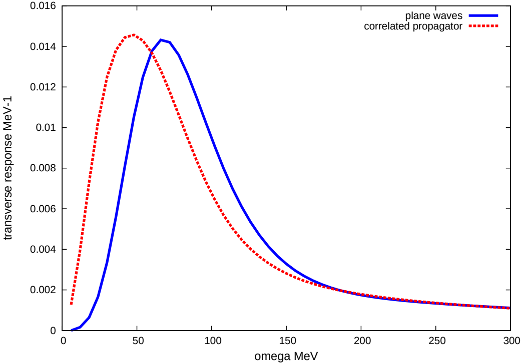
$$R_\alpha(q,\omega) \qquad \sim \int \delta\left(\omega + E_0 - E_f\right) d\Omega_P\, d\Omega_p\, dP\, dp \left[p^2\, P^2 \langle\, 0|O^\dagger_\alpha(\mathbf{q})|\mathbf{p},\mathbf{P}\rangle\langle\,\mathbf{p},\mathbf{P}|O_\alpha(\mathbf{q})|0\rangle\right]$$

* Preliminary results *

STA Transverse Response

$q = 300$ MeV

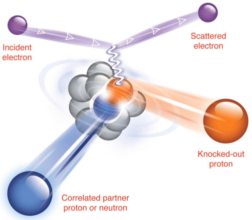
Plane Wave Propagator vs Correlated Propagator

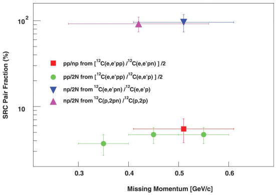


$$R_{\alpha}(q,\omega) \quad \sim \int \delta\left(\omega + E_0 - E_f\right) d\Omega_P \, d\Omega_p \, dP \, dp \left[p^2 P^2 \langle 0|O_{\alpha}^{\dagger}(\mathbf{q})|\mathbf{p},\mathbf{P}\rangle\langle \mathbf{p},\mathbf{P}|O_{\alpha}(\mathbf{q})|0\rangle\right]$$

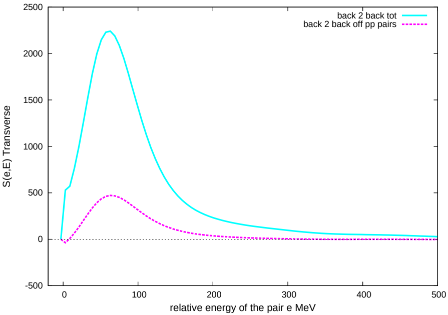
* Preliminary results *

STA back to back scattering



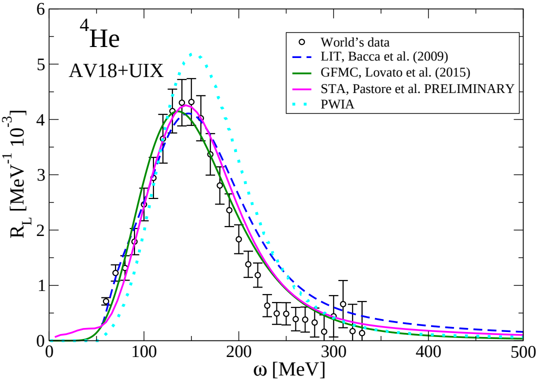


JLab, Subedi *et al.* Science320(2008)1475



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

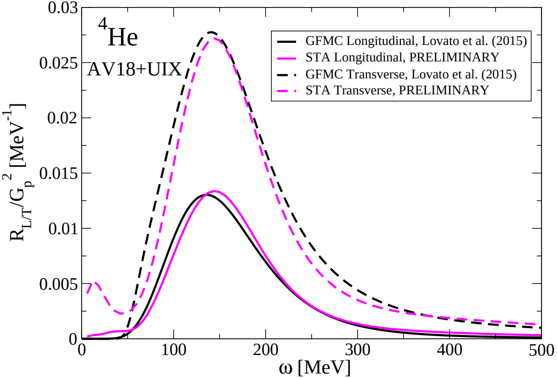
* Preliminary results *



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 υ-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 *