SRCs and Double Beta Decay

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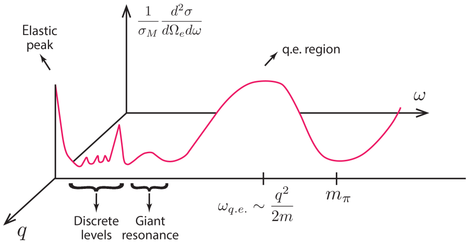
2nd Workshop on Quantitative Challenges in SRC and EMC Research
MIT March 2019

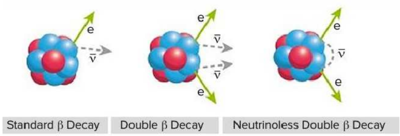
Washington University in St. Louis
Arts & Sciences

Carlson & Gandolfi (LANL)
Schiavilla (ODU+JLab) & Baroni (USC) & Piarulli (WashU) & Wiringa (ANL)
Mereghetti & Cirigliano & Graesser (LANL)
& Dekens (UCSD) & de Vries (Nikhef) & van Kolck (AU+CNRS/IN2P3)

Towards a coherent and unified picture of neutrino-nucleus interactions



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

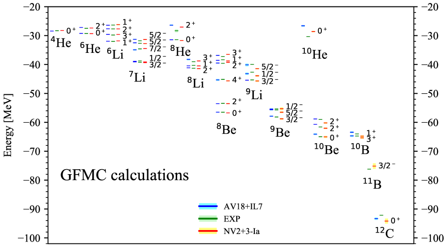


Nuclear Interactions

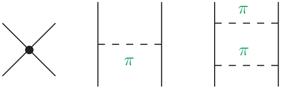
The nucleus is made of A non-relativistic interacting nucleons and its energy is

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

where υ_{ij} and V_{ijk} are two- and three-nucleon operators based on EXPT data fitting and fitted parameters subsume underlying QCD



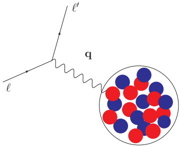
Piarulli *et al.* - PRL120(2018)052503



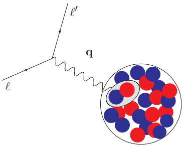
* QMC: AV18+UIX / AV18+IL7
Wiringa+Schiavilla+Pieper *et al.*
* QMC: NN(N2LO)+3N(N2LO) (π&N)
Gerzelis+Tews+Epelbaum+Gandolfi+Lynn *et al.*
* QMC: NN(N3LO)+3N(N2LO) (π&N&Δ)
Piarulli *et al.*

Nuclear Currents

1b



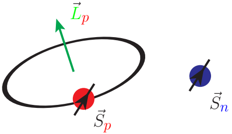
2b



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

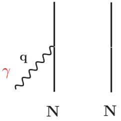
$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$

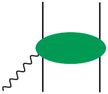
* Nuclear currents given by the sum of p's and n's currents, one-body currents (1b)



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

* We use Meson-Exchange Currents (MEC) or χEFT Currents

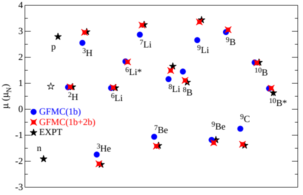


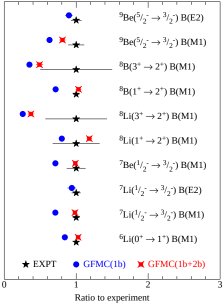


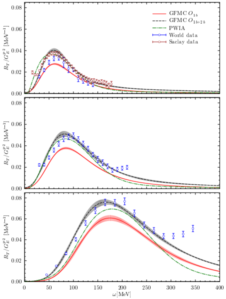
$+ \ \ldots$

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

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





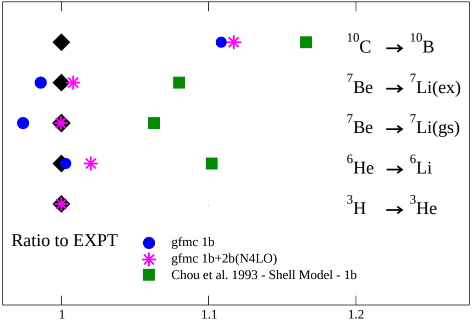


Pastore *et al.* PRC87(2013)035503

Lovato *et al.* PRC91(2015)062501

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

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

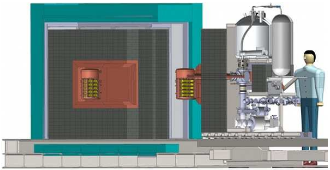
Based on $g_A \sim 1.27$ no quenching factor

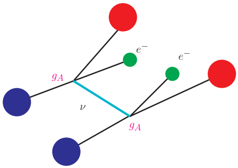
GT in ^{3}H is fitted to expt - 2b give a 2% additive contribution to 1b prediction

* similar results were obtained with MEC currents

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

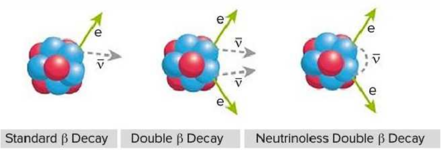
Neutrinoless Double Beta Decay



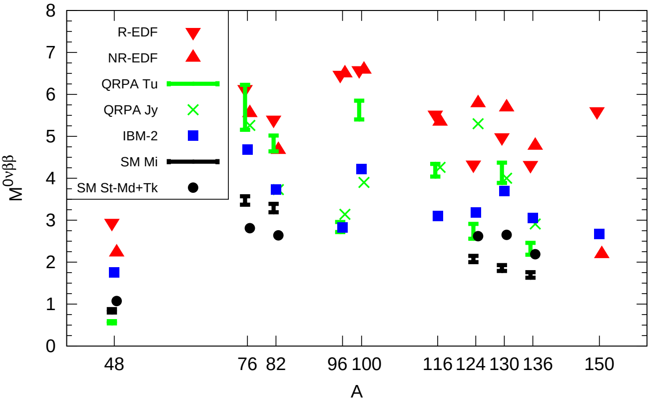


"The average momentum is about 100 MeV, a scale set by the average distance between the two decaying neutrons" cit. Engel&Menéndez

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

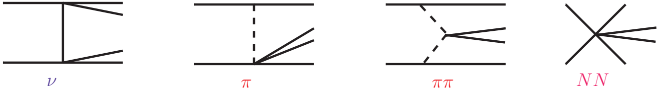


Neutrinoless Double Beta Decay: STATUS



Javier Menéndez - arXiv:1703.08921 (2017)

Double beta-decay 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 PRC97(2018)065501

Leading order operators are two-body operators

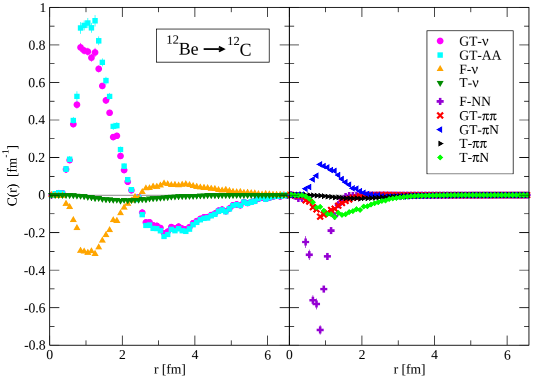
Understanding two-body physics, (correlation and currents) is crucial

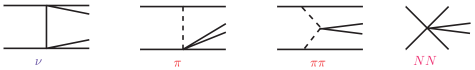
IN COLLABORATION WITH

Emanuele Mereghetti & Wouter Dekens & Cirigliano & Carlson & Wiringa

PRC97(2018)014606

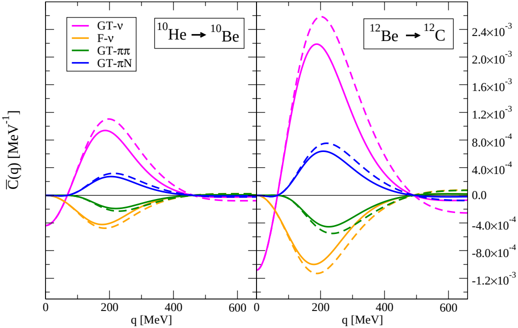
Double beta-decay Matrix Elements





PRC97(2018)014606

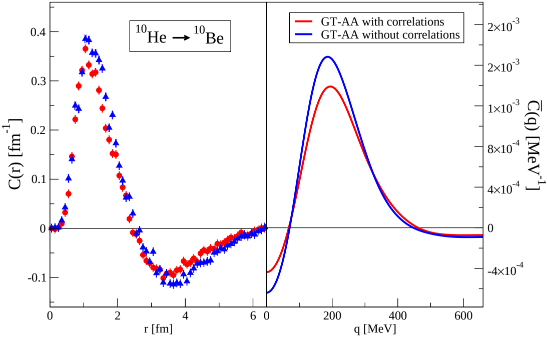
Momentum Dependence



* Peaks at $\sim$ 200 MeV
* $A = 10$ highly suppressed w.r.t. $A = 12$ (cluster structure matters?)
* $A = 12$ 'most similar' to experimental cases

PRC97(2018)014606

Sensitivity to ‘pion-exchange-like’ correlations

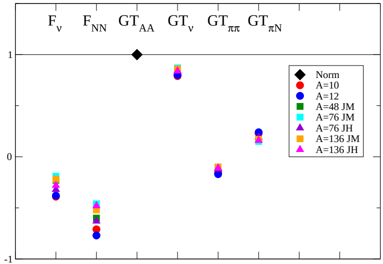


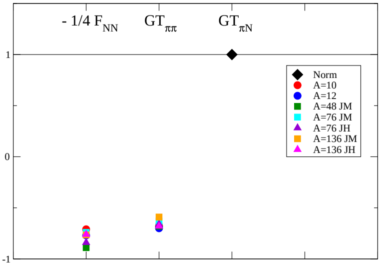
* no ‘pion-exchange-like’ correlations

* yes ‘pion-exchange-like’ correlations

PRC97(2018)014606

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

PRC97(2018)014606

Inclusive (e,ν) scattering

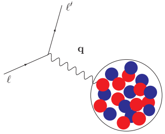
* inclusive xsecs *

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

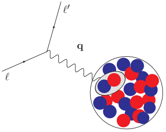
$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle f | O_\alpha(\mathbf{q}) | 0 \rangle|^2$$

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

1b



2b

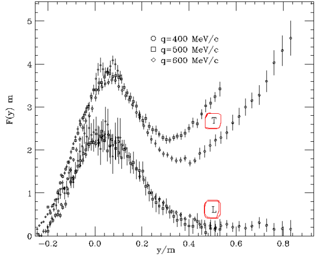


$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \dots\,,$$

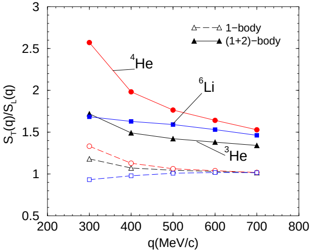
$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \dots$$

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

Longitudinal and transverse responses of ^{12}C

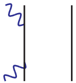


Benhar, Day, Sick Rev.Mod.Phys.80(2008)198, data Finn 1984

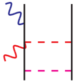


Carlson *et al.* PRC65(2002)024002

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



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



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

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

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

• two-body physics essential to explain the data •

Factorization

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

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

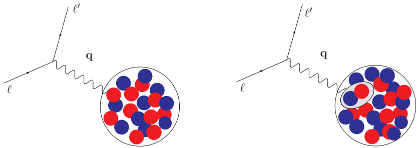
At short time, expand $P(t) = e^{i(H-\omega)t}$ and keep up to 2b-terms

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

and

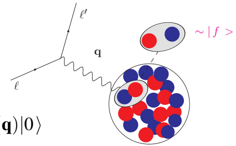
$$O_i^\dagger P(t) O_i + O_i^\dagger P(t) O_j + O_i^\dagger P(t) O_{ij} + O_{ij}^\dagger P(t) O_{ij}$$

1b 2b



Factorization up to two-body operators: The Short-Time Approximation (STA)

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



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

$$O(\mathbf{q}) = O^{(1)}(\mathbf{q}) + O^{(2)}(\mathbf{q}) = 1\text{b} + 2\text{b}$$
$$|f\rangle \sim |\psi_{p',P',J,M,L,S,T,M_T}(r,R)\rangle = \text{correlated two-nucleon w.f.}$$

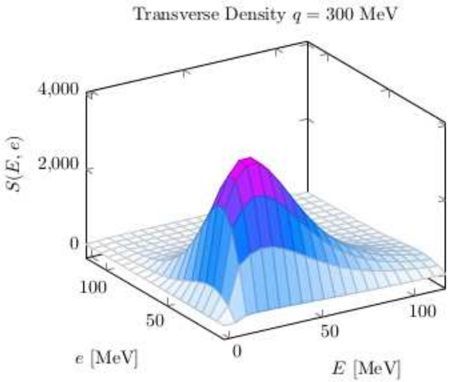
* We retain two-body physics consistently in the nuclear interactions and electroweak currents
* STA can describe pion-production induced by e and ν

* Definition: Response Density $\mathscr{D}$ *

$$R(q,\omega) \sim \int \delta\left(\omega + E_0 - E_f\right) d\Omega_{P'}\, d\Omega_{p'}\, dP'\, dp' \left[p^{2\prime} P^{2\prime} \langle 0|O^\dagger(\mathbf{q})|\mathbf{p}',\mathbf{P}'\rangle\langle \mathbf{p}',\mathbf{P}'|O(\mathbf{q})|0\rangle\right]$$
$$\sim \int \delta\left(\omega + E_0 - E_f\right) dP'\, dp'\, \mathscr{D}(\mathbf{p}',\mathbf{P}';\mathbf{q})$$

$\mathscr{D}(\mathbf{p}',\mathbf{P}';\mathbf{q})$ has **info on the nucleus soon after the probe interacts with the pair of nucleons**;
provides more "**exclusive**" info in terms of nucleon-pair kinematics;
correctly accounts for **interference** terms

Short-Time Approximation: Response Densities



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

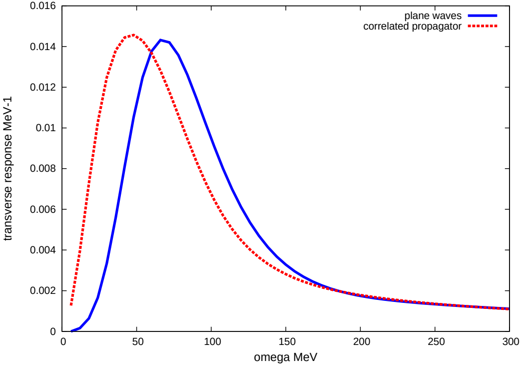
$\mathscr{D}(\mathbf{p}', \mathbf{P}'; \mathbf{q})$

* Preliminary results *

STA Transverse Response

$q = 300$ MeV

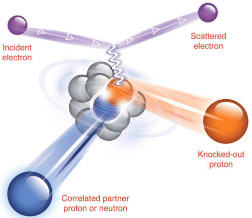
Plane Wave Propagator vs Correlated Propagator

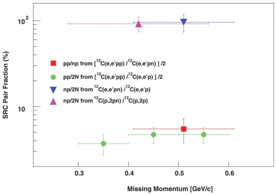


$$R_\alpha(q,\omega) \sim \int \delta(\omega + E_0 - E_f)\, d\Omega_P\, d\Omega_p\, dP\, dp \left[p^2 P^2 \langle 0 | O^\dagger_\alpha(\mathbf{q}) | \mathbf{p}, \mathbf{P} \rangle \langle \mathbf{p}, \mathbf{P} | O_\alpha(\mathbf{q}) | 0 \rangle \right]$$

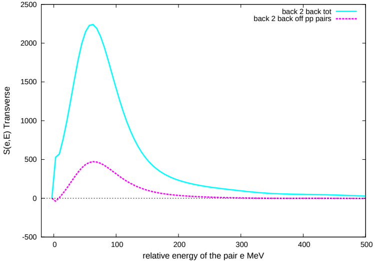
* Preliminary results *

Short-Time Approximation: back to back scattering





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

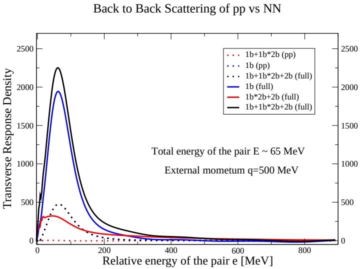


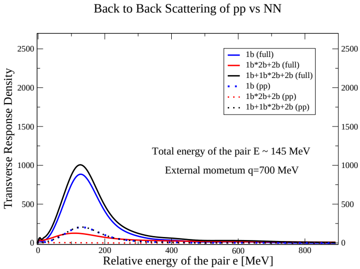
$q = 500$ MeV, $E = 65$ MeV *pp* vs tot

- Also relevant to semi-inclusive processes •

* Preliminary results *

Short-Time Approximation: back to back scattering





$\mathbf{j}_i \mathbf{j}_j$ = 1b

$\mathbf{j}_i \mathbf{j}_{ij} + \mathbf{j}_{ij} \mathbf{j}_{ij}$ = 1b*2b+2b

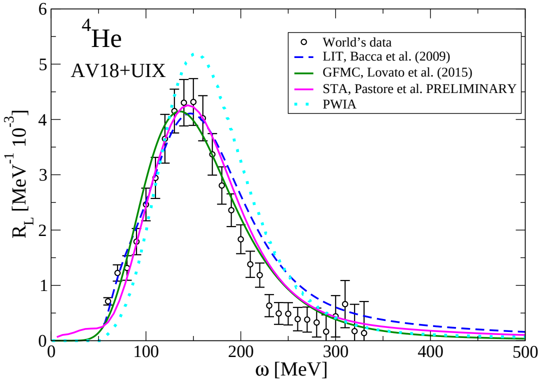
$\mathbf{j}_{tot}\ \mathbf{j}_{tot}$

solid lines = all pairs

dashed lines = proton-proton pairs

* Preliminary results *

Short-Time Approximation: Comparison with data and exact calculations

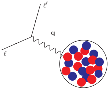


Longitudinal Response function at $q = 500$ MeV

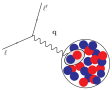
* Preliminary results *

Short-Time Approximation: Summary

1b



2b



What it is

* It is based on factorization at short-time
* **Retains two-body operators** correlating nucleon-pairs and associated two-body currents
* Describes the **scattering of leptons off pairs of fully interacting nucleons**
* Lepton-nucleus interaction occurs via 1b and 2b currents and ensuing **interference** terms
* It provides **response functions**
* It provides **response densities** as function of the relative and total energy of a nucleon-pair
* It can accommodate for **semi-inclusive processes**, **pion-production**, **relativity**
* It **can be implemented in AFDMC** to study $A \sim 40$ systems

Where we are

* Electromagnetic Response Functions and Densities of ^{4}He, ^{3}H and ^{3}He are available for values of $|\mathbf{q}|$ and $E \leq 800$ MeV

Work in progress

* Implementation of axial currents into VMC codes
* Implementation of the STA into VMC codes for ^{12}C