

Nuclear-Structure Corrections in Superaligned Beta Decay

Electroweak Transitions with Coupled-Cluster Theory

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Washington University in St. Louis

FRIB-TA, September 17, 2025



Outline

- 1 Motivation
- 2 EW Operators for δ_{NS}
- 3 Nuclear Structure from First Principles
- 4 Benchmarking and Validation
- 5 Preliminary Results and Outlook

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$$g_W \begin{array}{c} \text{ } \\ \swarrow \text{ } u \\ \searrow \text{ } d' \\ \bullet \\ \downarrow W^\pm \end{array} = g_{ud} \begin{array}{c} \text{ } \\ \swarrow \text{ } u \\ \searrow \text{ } d \\ \bullet \\ \downarrow W^\pm \end{array} + g_{us} \begin{array}{c} \text{ } \\ \swarrow \text{ } u \\ \searrow \text{ } s \\ \bullet \\ \downarrow W^\pm \end{array} + g_{ub} \begin{array}{c} \text{ } \\ \swarrow \text{ } u \\ \searrow \text{ } b \\ \bullet \\ \downarrow W^\pm \end{array}$$

CKM Matrix: $\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$



The diagram shows the decomposition of the \$W\$ boson coupling to a quark doublet. On the left, a vertex labeled \$g_W\$ connects an incoming \$u\$ quark line and an outgoing \$d'\$ quark line to a \$W^\pm\$ boson line. This is shown to be equal to the sum of three terms: 1) a vertex labeled \$g_{ud}\$ connecting \$u\$ and \$d\$ quarks to \$W^\pm\$, 2) a vertex labeled \$g_{us}\$ connecting \$u\$ and \$s\$ quarks to \$W^\pm\$, and 3) a vertex labeled \$g_{ub}\$ connecting \$u\$ and \$b\$ quarks to \$W^\pm\$.

CKM Matrix: $\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$

SM (Unitarity): $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \pm 10^{-3}$?



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CKM Matrix: $\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$

SM (Unitarity): $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \pm 10^{-3}$?

$|V_{ud}| \approx 0.97 \pm ??$ from: Neutron Decay, Mirror Beta Decay, Pion Beta Decay,
or Superallowed Beta Decay?

Measuring CKM Unitarity

- Neutron Decay: Well-known Q-value and BR, no nuclear-structure or isospin corrections.
Needs precise $T_{1/2}$ and correlation measurements. Hard to handle.
- Mirror Decay: Easy-to-handle generalization of Neutron Decay.
Needs additional isospin and nuclear-structure corrections.
- Pion Decay: $\pi^+ \rightarrow \pi^0 e^+ \nu_e$, Pure vector transition without nuclear-structure corrections.
Extremely rare with BR of $\sim 10^{-8}$.
- Superaligned Decay: $0^+ \rightarrow 0^+$, Pure vector transition with easily handled isotopes.
Requires isospin and nuclear-structure corrections.

-
- Figure 1 consists of a main plot and three inset plots. The main plot shows the value of V_{ud} for four different cases: nuclear $0^+ \rightarrow 0^+$, neutron, nuclear mirrors, and pion. The y-axis ranges from 0.9700 to 0.9800. The x-axis labels are 'nuclear $0^+ \rightarrow 0^+$ ', 'neutron', 'nuclear mirrors', and 'pion'. The legend indicates three data series: Experiment (dark grey), Radiative correction (medium grey), and Nuclear correction (light grey). The main plot shows the experimental values with error bars. The three inset plots show the radiative and nuclear corrections for each case. The radiative correction is shown as a dark grey bar, and the nuclear correction is shown as a light grey bar. The y-axis for the insets is 'Uncertainty' ranging from 0.001 to 0.003.

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V_{ud} from Superaligned β -Decays

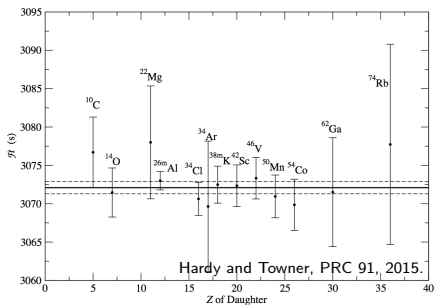
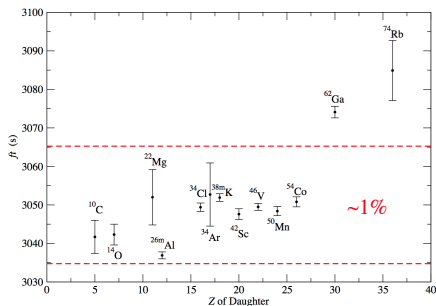
$$\frac{1}{ft} = \frac{G_F^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} (1 + \Delta_R^V) (1 + \delta'_R) (1 - \delta_C + \delta_{NS}) \quad \frac{1}{\mathcal{F}t} = \frac{G_F^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2}$$

V_{ud} from Superallowed β -Decays

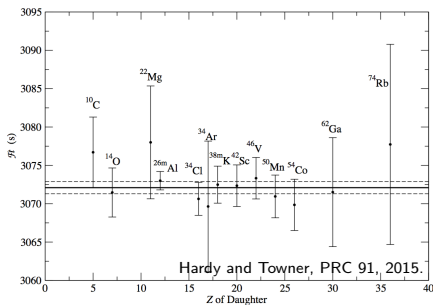
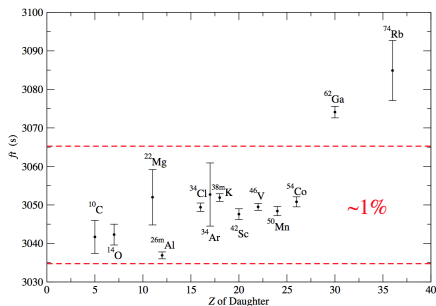
$$\frac{1}{ft} = \frac{G_F^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} \left(\overset{\text{Single-Nucleon}}{\underbrace{(1 + \Delta_R^V)}} \overset{\text{Outer-Correction}}{\underbrace{(1 + \delta'_R)}} \overset{\text{Isospin}}{\underbrace{(1 - \delta_C + \delta_{NS})}} \right) \quad \frac{1}{\mathcal{F}t} = \frac{G_F^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2}$$

- **Single-Nucleon:** Short-distance electroweak loop effects, universal to all decays
- **Outer-Correction:** QED correction depending on electron energy and nuclear charge
- **Isospin:** Accounts for imperfect isospin symmetry in real nuclei
- **Nucleus-Dependent:** Radiative correction sensitive to internal nuclear structure

$$\frac{1}{ft} = \frac{G_F^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} \underbrace{(1 + \Delta_R^V)}_{\text{Single-Nucleon}} \underbrace{(1 + \delta'_R)}_{\text{Outer-Correction}} \underbrace{(1 - \delta_C + \delta_{NS})}_{\text{Isospin Nucleus-Dependent}} \quad \frac{1}{\mathcal{F}t} = \frac{G_F^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2}$$



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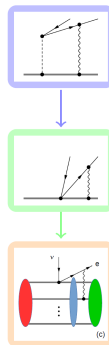


- Improve V_{ud} from superallowed β -decays by calculating δ_{NS} for various nuclei.
- We need an **ab initio method** and an **effective EW theory** for higher-order interactions.

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Ab initio electroweak corrections to superallowed β decays and their impact on V_{ud}

Martin Hoferichter ⁵ and Emanuele Mereghetti ⁴



Ab initio electroweak corrections to superallowed β decays and their impact on V_{ud}

The diagram illustrates a multi-scale approach for beta-decay rate predictions, organized into four energy scales on the left and three photon mode regions on the right.

Effective theories and interactions (Left Column):

- SM (Standard Model):** Includes QED + QCD and Weak interactions.
- LEFT:** QED + QCD and $u \rightarrow d\nu_e e^+$ operator $\sim C_\beta$.
- χ^2 PT (Chiral Perturbation Theory):** QED_{3PT}, $p \rightarrow n\nu_e e^+$ operator $\sim g_V$, and $pN \rightarrow nN\nu_e e^+$ operators $\sim g_{\pi^0, \pi^\pm}^{(1,2)}$.
- χ^2 EFT (Chiral Effective Field Theory):** QED_{4EFT}, $p \rightarrow n\nu_e e^+$ operator $\sim C_{\text{eff}}^{(3,1)}$, and $pN \rightarrow nN\nu_e e^+$ potentials $\mathcal{V}_i$.

Active photon modes (Right Column):

- Hard:** $q_0 \sim |q| \gtrsim m_\nu$. Integrates out heavy SM fields.
- Soft:** $q_0 \sim |q| \sim M_\pi$. Non-perturbative matching LQCD/Dispersive methods.
- Potential:** $|q| \sim M_\pi \gg q_0 \sim Q$. Integrates out soft & potential photons.
- Ultrasoft:** $q_0 \sim |q| \sim Q$. Many-body calculations, Nuclear matrix elements.

Bottom Section (Common to all):

- Fermi function $\bar{F}$ & $\bar{g}_C$:** Outer correction $\bar{g}_R$.
- Evolution from μ_H to $\mu_{\text{ew}} \sim C_{\text{eff}}^{(3,1)}$.**
- Nuclear-structure dependence $\bar{g}_{NS}$.**

Final Output: β -decay rate predictions.

$$Q \ll M_\pi \ll M_N \ll M_W$$

Exploit different separation of scales to write correction as expansion in α and Q/Λ_χ

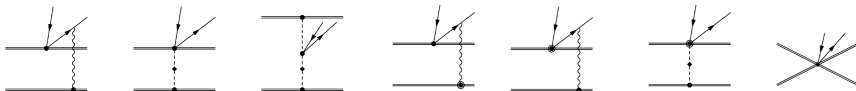
Effective Field Theory for Radiative Corrections

PHYSICAL REVIEW C **110**, 055502 (2024)

Ab initio electroweak corrections to superallowed β decays and their impact on V_{ud}

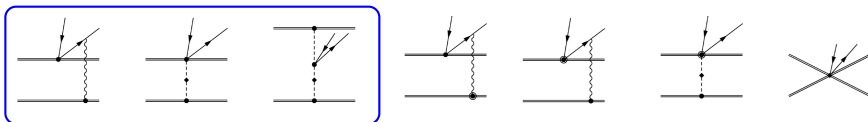
Vincenzo Cirigliano¹, Wouter Dekens¹, Jordy de Vries^{2,3}, Stefano Gandolfi⁴,

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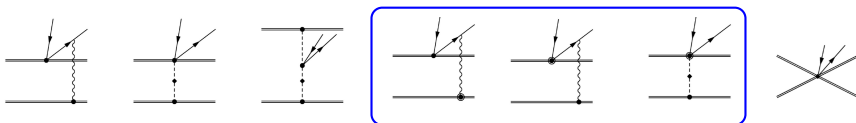
- Leading-order EM and Weak interactions, $\mathcal{O}(\alpha q_{ex}/M_\pi)$
- Energy-dependent, proportional to external momentum
- Replaces charge-radius corrections, grows with A

Effective Field Theory for Radiative Corrections

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- NLO EW interactions, $\mathcal{O}(\alpha M_\pi/\Lambda_\chi)$
- Energy-independent, Long-range
- Corrections from magnetic moments and recoil
- Induces UV sensitivity and cutoff dependence

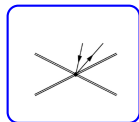
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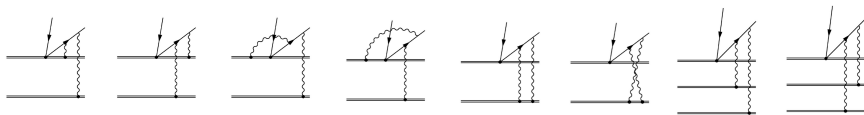
- Cutoff dependence absorbed by contact terms, $\mathcal{O}(F_\pi^{-2} \Lambda_\chi^{-1})$
- LECs could be extracted from LQCD or other models
- Can also be used as free parameters for a global V_{ud} fit

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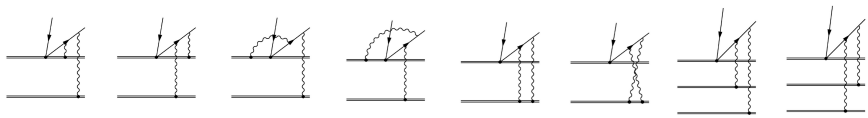
- Mixed-scale photons important for required precision, $\mathcal{O}(\alpha^2)$
- Include corrections to Fermi function
- Soft photons also induce three-body terms (excluded for now)

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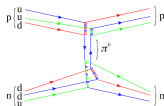
- Mixed-scale photons important for required precision, $\mathcal{O}(\alpha^2)$
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$$M_{\beta,k=p,n}^{\mathcal{O}} = \int d\vec{r}_{ij} \langle \mathcal{F} | \sum_{i < j} \hat{h}_{\beta,k=p,n}^{\mathcal{O}}(r_{ij}) \left[\tau_i^+ \hat{P}_j^k + (i \leftrightarrow j) \right] | \mathcal{I} \rangle, \quad \beta = \text{F, GT, T, SO}$$

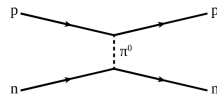
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1) Nuclear Interaction

Chiral Effective Field Theory:

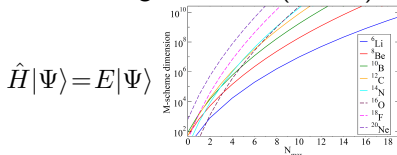


$$\left(\frac{Q}{\Lambda}\right)$$



2) Many-body Quantum Mechanics

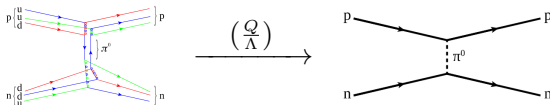
Direct Diagonalization (NCSM):



“Ab Initio” Nuclear Theory

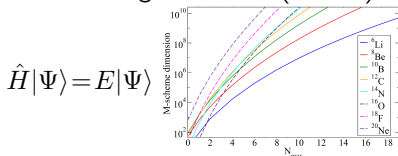
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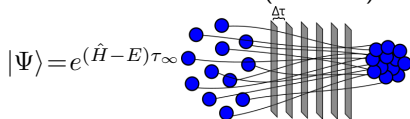


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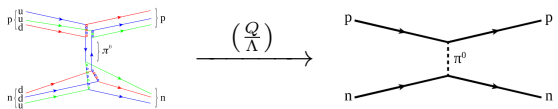
Stochastic Methods (AFDMC):



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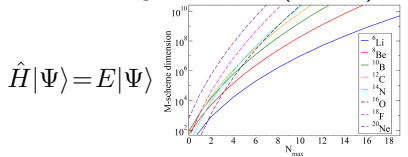
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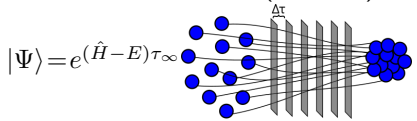


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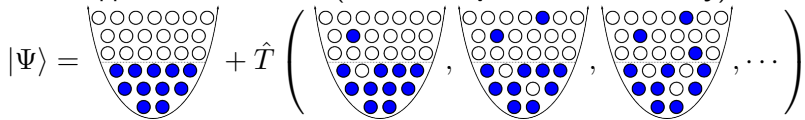
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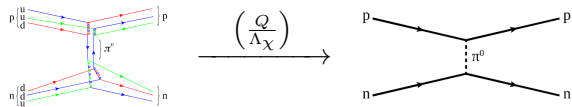
Approximate Methods (MBPT, **Coupled Cluster Theory**):



Chiral Effective Field Theory

1) Nuclear Interaction

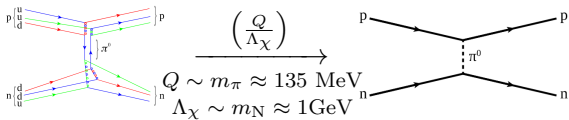
Chiral Effective Field Theory:



Chiral Effective Field Theory

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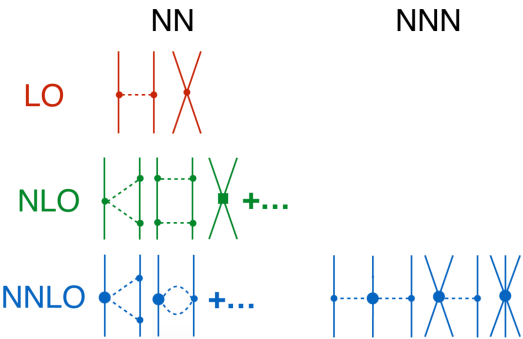
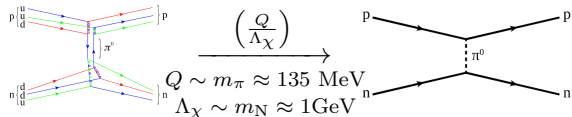
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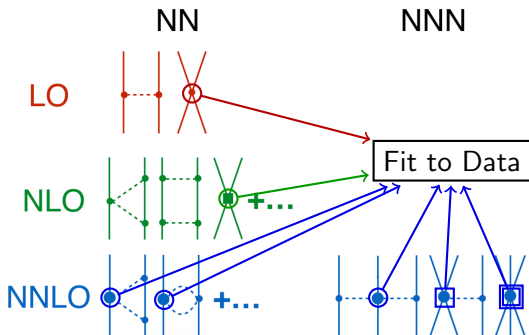
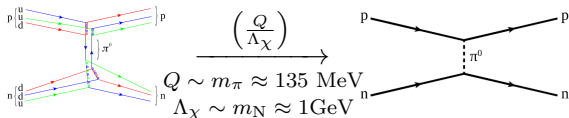
$$\begin{aligned}
 & \underbrace{V_{1\pi} + V_{ct}^{(0)}}_{(Q/\Lambda_\chi)^0} \\
 & + \underbrace{V_{2\pi}^{(2)} + V_{ct}^{(2)}}_{(Q/\Lambda_\chi)^2} \\
 & + \underbrace{V_{2\pi}^{(3)} + V_{2\pi}^{3N} + V_{1\pi}^{3N} + V_{ct}^{3N}}_{(Q/\Lambda_\chi)^3} + \dots
 \end{aligned}$$

W.G. Jiang, et al. 2020. Phys. Rev. C 102, 054301.

Chiral Effective Field Theory

1) Nuclear Interaction

Chiral Effective Field Theory:



$$\begin{aligned}
 & \underbrace{V_{1\pi} + V_{\text{ct}}^{(0)}}_{(Q/\Lambda_\chi)^0} \\
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 \end{aligned}$$

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Coupled-Cluster Theory

Exponential Ansatz: $|\Psi\rangle = e^{\hat{T}} |\Phi_0\rangle$

$$|\Phi_0\rangle \equiv \text{diagram} \quad \hat{T} \equiv \sum_{1p1h} t_1 \text{diagram} + \sum_{2p2h} t_2 \text{diagram} + \sum_{3p3h} t_3 \text{diagram} + \dots$$

The diagrams represent particle-hole excitations in a shell model. The first diagram shows the ground state $|\Phi_0\rangle$ with 10 particles (blue dots) in the lowest 10 orbitals of a harmonic well. The subsequent diagrams show the components of the excitation operator $\hat{T}$: a single-particle, single-hole excitation ($1p1h$), a double-particle, double-hole excitation ($2p2h$), and a triple-particle, triple-hole excitation ($3p3h$), each with its corresponding coefficient t_1, t_2, t_3 .

Coupled-Cluster Theory

Exponential Ansatz: $|\Psi\rangle = e^{\hat{T}} |\Phi_0\rangle$

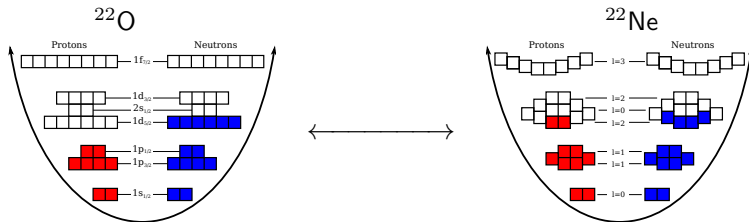
$$|\Phi_0\rangle \equiv \begin{array}{c} \text{Diagram: A bowl containing 16 white circles and 8 blue circles at the bottom.} \end{array} \quad \hat{T} \equiv \sum_{1p1h} t_1 \begin{array}{c} \text{Diagram: A bowl containing 16 white circles and 8 blue circles at the bottom.} \end{array} + \sum_{2p2h} t_2 \begin{array}{c} \text{Diagram: A bowl containing 16 white circles and 8 blue circles at the bottom.} \end{array} + \sum_{3p3h} t_3 \begin{array}{c} \text{Diagram: A bowl containing 16 white circles and 8 blue circles at the bottom.} \end{array} + \dots$$

CC Hamiltonian: $\bar{H} \equiv e^{-\hat{T}} \hat{H} e^{\hat{T}}$

- Decouple excitations: $\langle \Phi' | \bar{H} | \Phi_0 \rangle \rightarrow 0$
- Correlated ground state: $\langle \Phi_0 | \bar{H} | \Phi_0 \rangle \rightarrow E_{\text{gs}}$
- Scales polynomially
- Anti-Hermitian Hamiltonian

$\langle \Phi_0 \hat{H} \Phi_0 \rangle$	$\langle \Phi_0 \hat{H} \Phi_h^p \rangle$	$\langle \Phi_0 \hat{H} \Phi_{hh}^{pp} \rangle$	$\langle \Phi_0 \hat{H} \Phi_{hhh}^{ppp} \rangle$
$\langle \Phi_h^p \hat{H} \Phi_0 \rangle$	$\langle \Phi_h^p \hat{H} \Phi_h^p \rangle$	$\langle \Phi_h^p \hat{H} \Phi_{hh}^{pp} \rangle$	$\langle \Phi_h^p \hat{H} \Phi_{hhh}^{ppp} \rangle$
$\langle \Phi_{hh}^{pp} \hat{H} \Phi_0 \rangle$	$\langle \Phi_{hh}^{pp} \hat{H} \Phi_h^p \rangle$	$\langle \Phi_{hh}^{pp} \hat{H} \Phi_{hh}^{pp} \rangle$	$\langle \Phi_{hh}^{pp} \hat{H} \Phi_{hhh}^{ppp} \rangle$
$\langle \Phi_{hhh}^{ppp} \hat{H} \Phi_0 \rangle$	$\langle \Phi_{hhh}^{ppp} \hat{H} \Phi_h^p \rangle$	$\langle \Phi_{hhh}^{ppp} \hat{H} \Phi_{hh}^{pp} \rangle$	$\langle \Phi_{hhh}^{ppp} \hat{H} \Phi_{hhh}^{ppp} \rangle$

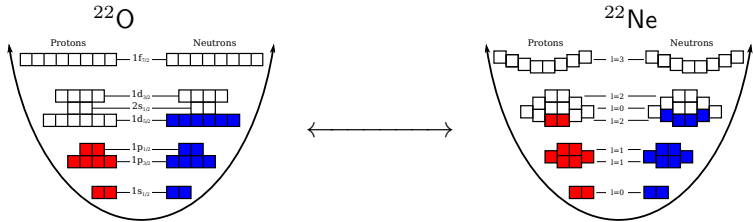
Deformed Coupled Cluster Theory



- Restricted to closed-shell, Spherical
- $\hat{J}^2$ is good quantum number
- Computational discount

- Unrestricted, Quadrupole Deformation
- $\hat{J}_z$ is good quantum number
- Computational penalty

Deformed Coupled Cluster Theory



- | | |
|--|--|
| <ul style="list-style-type: none"> ● Restricted to closed-shell, Spherical ● $\hat{J}^2$ is good quantum number ● Computational discount | <ul style="list-style-type: none"> ● Unrestricted, Quadrupole Deformation ● $\hat{J}_z$ is good quantum number ● Computational penalty |
|--|--|

Now, all nuclei can be reached with minimal error from the broken symmetry.

PHYSICAL REVIEW C **105**, 064311 (2022)

Angular-momentum projection in coupled-cluster theory: Structure of ^{34}Mg

G. Hagen, **S.J. Novario**, Z. H. Sun, and T. Papenbrock

Odd-Odd State: Equation-of-motion method

EOM method builds biorthogonal eigenvectors of $\bar{H}$ on the closed-shell ground state,

$$\bar{H} \hat{R}_\mu |\Phi_0\rangle = E_\mu \hat{R}_\mu |\Phi_0\rangle \quad \hat{R} \equiv r_0 + \sum_{1p1h} r_1 \begin{array}{c} \text{diagram of 1p1h excitation} \end{array} + \sum_{2p2h} r_2 \begin{array}{c} \text{diagram of 2p2h excitation} \end{array} + \dots \sim \hat{L}^\dagger$$

$\langle \Phi_0 \hat{H} \Phi_0 \rangle$	$\langle \Phi_0 \hat{H} \Phi_h^p \rangle$	$\langle \Phi_0 \hat{H} \Phi_{hh}^{pp} \rangle$	$\langle \Phi_0 \hat{H} \Phi_{hhh}^{ppp} \rangle$
$\langle \Phi_h^p \hat{H} \Phi_0 \rangle$	$\langle \Phi_h^p \hat{H} \Phi_h^p \rangle$	$\langle \Phi_h^p \hat{H} \Phi_{hh}^{pp} \rangle$	$\langle \Phi_h^p \hat{H} \Phi_{hhh}^{ppp} \rangle$
$\langle \Phi_{hh}^{pp} \hat{H} \Phi_0 \rangle$	$\langle \Phi_{hh}^{pp} \hat{H} \Phi_h^p \rangle$	$\langle \Phi_{hh}^{pp} \hat{H} \Phi_{hh}^{pp} \rangle$	$\langle \Phi_{hh}^{pp} \hat{H} \Phi_{hhh}^{ppp} \rangle$
$\langle \Phi_{hhh}^{ppp} \hat{H} \Phi_0 \rangle$	$\langle \Phi_{hhh}^{ppp} \hat{H} \Phi_h^p \rangle$	$\langle \Phi_{hhh}^{ppp} \hat{H} \Phi_{hh}^{pp} \rangle$	$\langle \Phi_{hhh}^{ppp} \hat{H} \Phi_{hhh}^{ppp} \rangle$

$$\langle \Phi_0 | \hat{L}_\mu \bar{H} = \langle \Phi_0 | \hat{L}_\mu E_\mu$$

$$\langle \Phi_0 | \hat{L}_\mu \hat{R}_\mu | \Phi_0 \rangle = 1$$

$\hat{R}, \hat{L}$ target appropriate quantum numbers, $\tau_\pm$ for charge-exchange.

$$\bar{O} \equiv e^{-\hat{T}} \hat{O} e^{\hat{T}} \quad |M_\beta|^2 = \langle \Phi_0 | \hat{L}_0 \bar{O}^\dagger \hat{R}_k | \Phi_0 \rangle \langle \Phi_0 | \hat{L}_k \bar{O} | \Phi_0 \rangle$$

Figure 1 consists of two vertically stacked panels sharing a common x-axis representing different nuclei: ${}^4\text{He}$, ${}^8\text{He}$, ${}^{14}\text{C}$, ${}^{16}\text{O}$, ${}^{40}\text{Ca}$, ${}^{48}\text{Ca}$, and ${}^{56}\text{Ni}$. The top panel displays the binding energy per nucleon E/A in MeV, ranging from -4 to -9. The bottom panel displays the charge radius Δr_{ch} in fm, ranging from 0.0 to -0.6. In both panels, experimental data are represented by black horizontal lines with error bars. NNLO_{sat} predictions are shown as red diamonds. Blue shaded vertical regions indicate the range of NNLO_{sat} predictions for each nucleus. A legend in the top right corner identifies the black line as 'Expt.'.

G. Hagen et al 2016 Phys. Scr. 91 063006

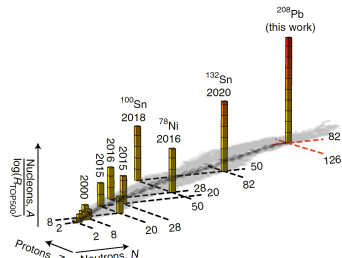
Figure 1 consists of a main plot and an inset. The main plot shows the charge density ρ_{ch} (in fm^{-3}) on the y-axis (ranging from 0.00 to 0.10) versus the radius r (in fm) on the x-axis (ranging from 0 to 8). It includes experimental data (green shaded region) and theoretical calculations for ^{40}Ca (black line), ^{48}Ca (red line), and the difference ΔCa (blue line). The inset plot shows $r^2 \Delta\rho_{ch}$ (in fm^{-1}) on the y-axis (ranging from -0.02 to 0.01) versus r (in fm) on the x-axis (ranging from 0 to 8). The inset highlights the difference between the ^{40}Ca and ^{48}Ca theoretical models, with the blue line representing ΔCa .

G. Hagen et al. Nat. Phys. 12, 186 (2016).

A. Ekström et al. Phys. Rev. C 91, 051301(R) (2015).

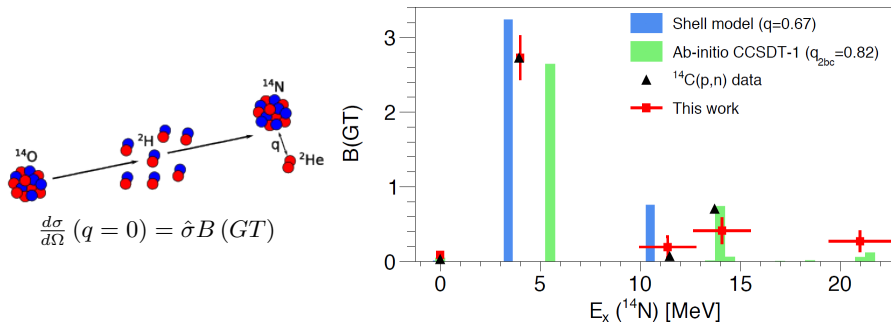
E_x [MeV]	B [G] (Shell model)	B [G] (Ab-initio CCSDT-1)	B [G] ($^{12}\text{C}(p,n)$ data)	B [G] (This work)
0	0.1	0.1	0.1	0.1
4	3.2	2.6	2.9	2.9
11	0.8	0.2	0.2	0.2
13	0.2	0.5	0.7	0.5
21	0.1	0.1	0.1	0.3

S. Giraud et al. Phys. Rev. Lett. 130, 232301 (2023).



Hu, B et al. Nat. Phys. 18, 1196–1200 (2022).

Experiment: Charge-Exchange Reaction $^{14}\text{O}(d, ^2\text{He})$



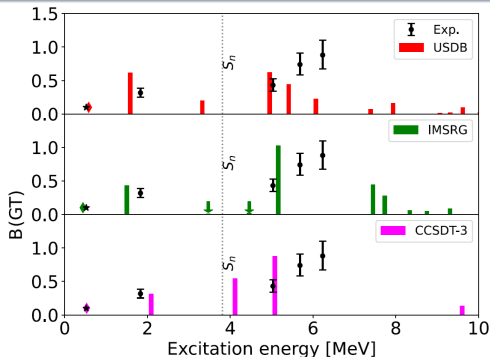
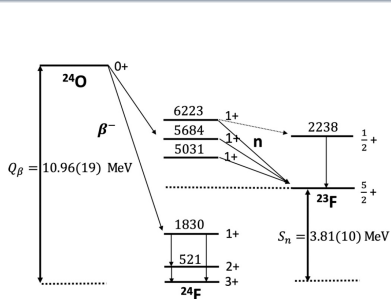
Phys. Rev. Lett. 130, 232301(2023)

β^+ Gamow-Teller strengths from unstable ^{14}O via the $(d, ^2\text{He})$ reaction in inverse kinematics

S. Giraud,^{1,2,3,*} J. C. Zamora,¹ R. Zegers,^{1,2,3,†} D. Bazin,^{1,3} Y. Ayyad,^{4,1} S. Bacca,^{5,6} S. Beccero-Novo,³ Maher,^{1,2,3} W. Mittig,^{1,3} F. Ndayisabye,^{1,2,3} S. Noji,¹ **S. J. Novario**, J. Pereira,^{1,2} Z. Rahman,^{1,2,3} J.

- Charge-exchange experiment with the AT-TPC and S800 Spectrograph (FRIB)
- Calculations match experiment by including effective 2BCs
- Gamow-Teller strength function reveals nuclear structure of ^{14}N
- Method to study Gamow-Teller distributions in unstable nuclei

Experiment: β -Delayed Spectrum from ^{24}O



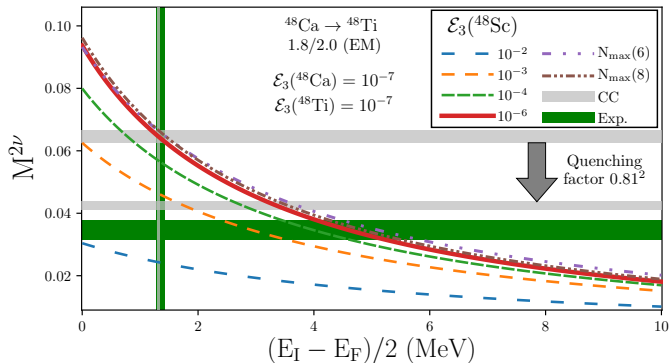
PHYSICAL REVIEW C **110**, 034323 (2024)

First β -delayed neutron spectroscopy of ^{24}O

S. Neupane,^{1,2,*} N. Kitamura,^{1,3} Z. Y. Xu,¹ R. Grzywacz,^{1,4} **S.J. Novario**, J. Okolowicz,^{6,7} M. Płoszajczak,⁷
 B. S. Hu,^{8,4} J. M. Allmond,⁴ A. Chester,⁹ J. M. Christie,¹ I. Cox,¹ J. Farr,¹ I. Fletcher,¹ J. Heideman,¹
 D. Hoskins,¹ T. T. King,¹ A. Laminack,⁴ S. N. Liddick,^{9,10} M. Madurga,¹ A. L. Richard,⁹ P. Shuai,^{1,4} K. Siegl,¹
 P. Wagenknecht,⁴ and R. Yokoyama¹

- β -delayed neutron spectrum with VANDLE and CALRION (NSCL)
- Calculations match experiment only at low energies
- High-order proton correlations and continuum coupling missing

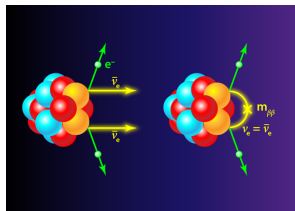
$2\nu\beta\beta$ decay of ^{48}Ca



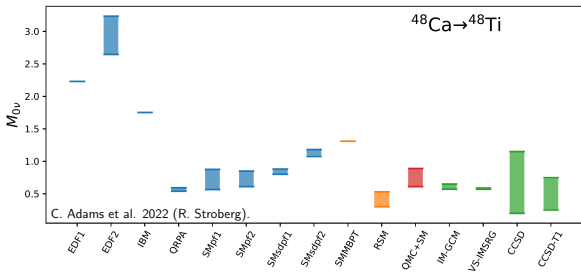
$$|M^{2\nu}|^2 = \left| \sum_{\mu} \frac{\langle f | \hat{O} | 1_{\mu}^{+} \rangle \langle 1_{\mu}^{+} | \hat{O} | i \rangle}{E_{\mu} - E_i + Q_{\beta\beta}/2} \right|^2 \propto T_{1/2}^{-1}$$

Two-body currents decreases NME, but still too large,
likely due to deformation of ^{48}Ti .

Beyond Standard Model: $0\nu\beta\beta$ Decay of ^{48}Ca



APS/Alan Stonebraker



PHYSICAL REVIEW LETTERS **126**, 182502 (2021)

Coupled-Cluster Calculations of Neutrinoless Double- β Decay in ^{48}Ca

S. J. Novario, P. Gysbers,^{3,4} J. Engel,⁵ G. Hagen,^{2,3,5} G. R. Jansen,^{6,2} T. D. Morris,² P. Navrátil,³
T. Papenbrock,^{6,1,2} and S. Quaglioni^{6,2}

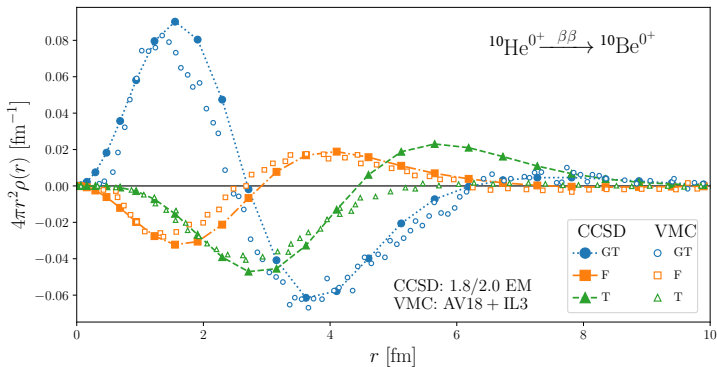
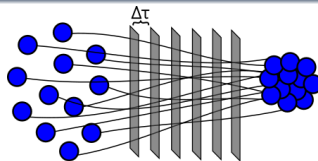
- $0\nu\beta\beta$ MEs for ^{48}Ca smaller with *ab initio* methods
- First estimation of unknown contact interaction
- Coupled cluster calculations in spherical and deformed bases
- $2\nu\beta\beta$ calculation agrees with experiment

$0\nu\beta\beta$ Decays: New Models

PHYSICAL REVIEW C **97**, 014606 (2018)

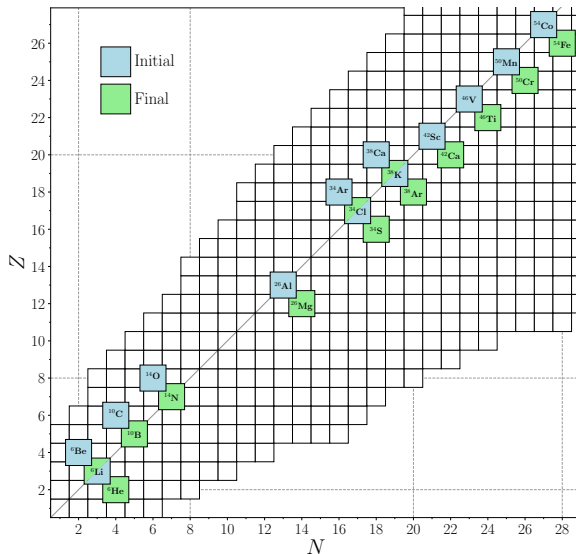
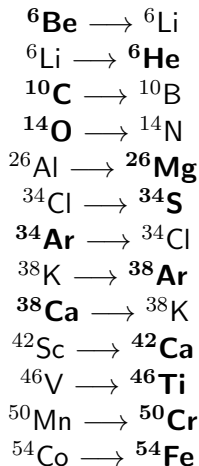
Neutrinoless double- β decay matrix elements in light nuclei

S. Pastore,¹ J. Carlson,¹ V. Cirigliano,¹ W. Dekens,^{1,2} E. Mereghetti,¹ and R. B. Wiringa³

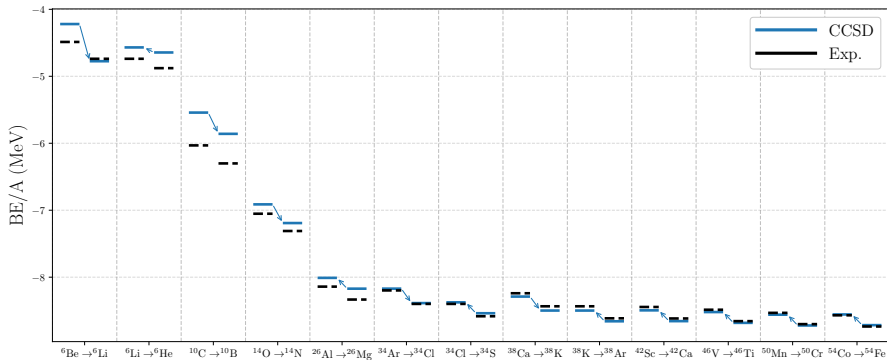


- 1 Motivation
- 2 EW Operators for δ_{NS}
- 3 Nuclear Structure from First Principles
- 4 Benchmarking and Validation**
- 5 Preliminary Results and Outlook

Superaligned Target Nuclei

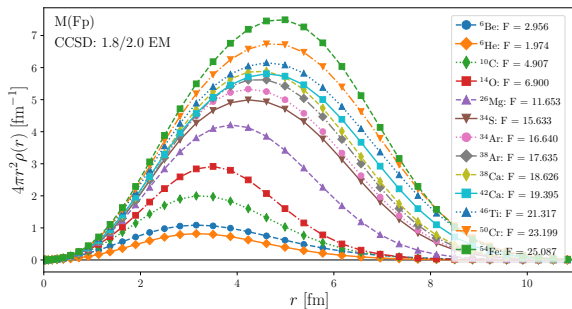
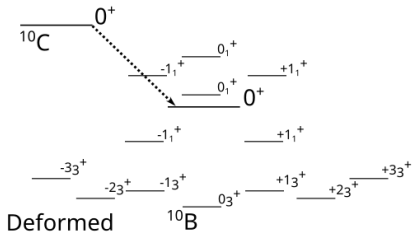
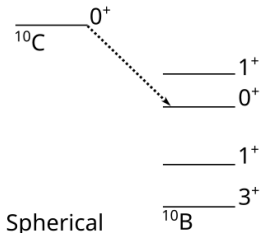


Results: Binding Energies



- Binding energies for parent and daughter from CC
- Requires triples correlations (CCSDT-1)
- Deformed CC BE results improve with A

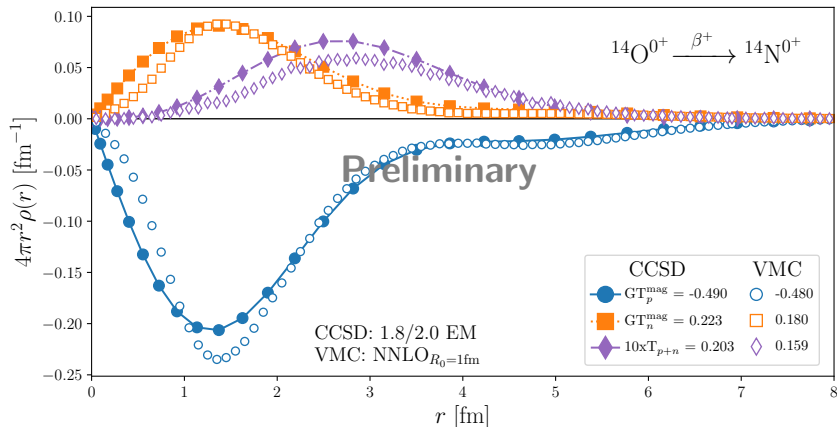
Deformed Transition Target State



$$\hat{O}_{F,p} = \tau_i^+ \hat{P}_j^p + (i \leftrightarrow j)$$

$$M_{F,p} = \int_0^\infty dr \langle \mathcal{F} | \hat{O}_{F,p}(r) | \mathcal{I} \rangle$$

Superaligned: $^{14}\text{O} \rightarrow ^{14}\text{N}$

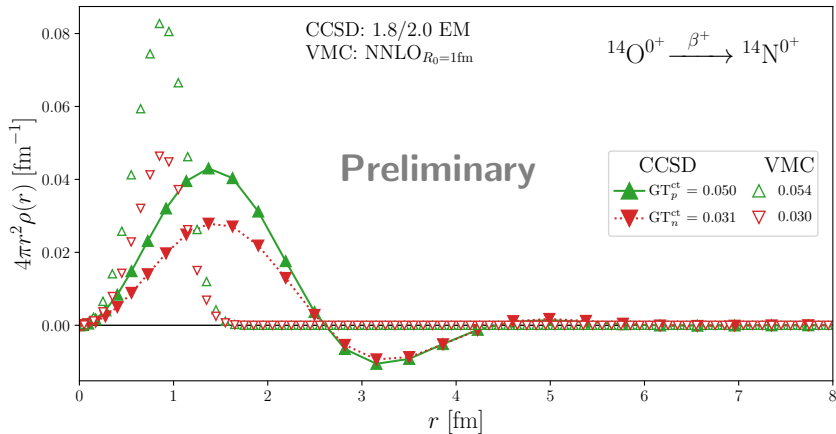


$T = 1$ transition. Closed-shell reference state: J-scheme.

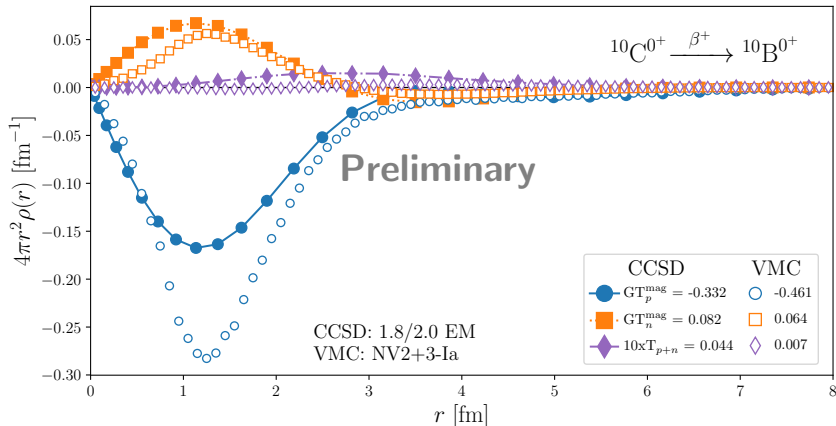
Gamow-Teller components dominate over tensor.

Short-range behavior doesn't agree likely due to interaction regulation.

Superaligned: $^{14}\text{O} \rightarrow ^{14}\text{N}$

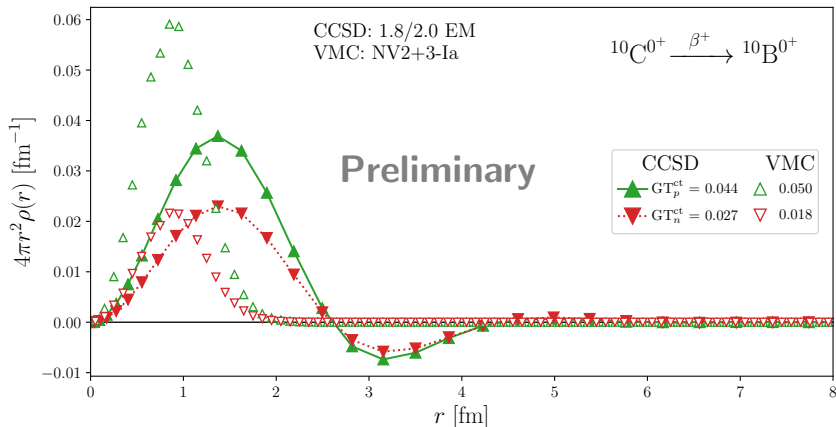


Regulation: $\delta(r) \propto e^{-r^4/R_0^4}$ vs. $f_\Lambda(r) \propto \int dk k^2 j_l(kr) f_\Lambda(k)$

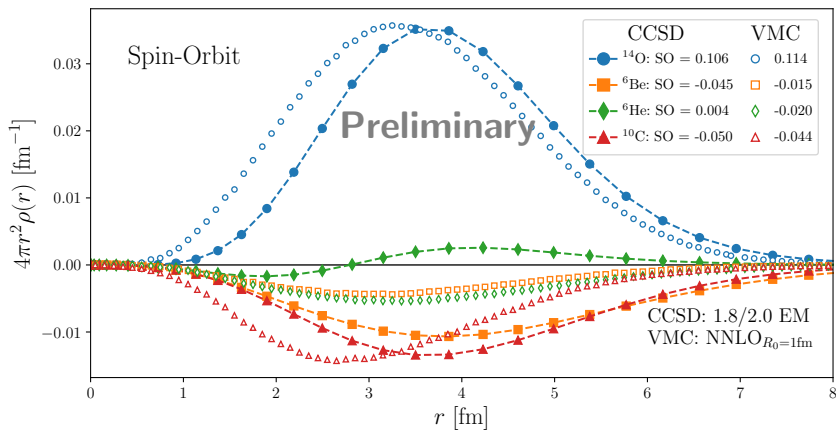


Deformation probably causes disagreements. Add triples correlations?

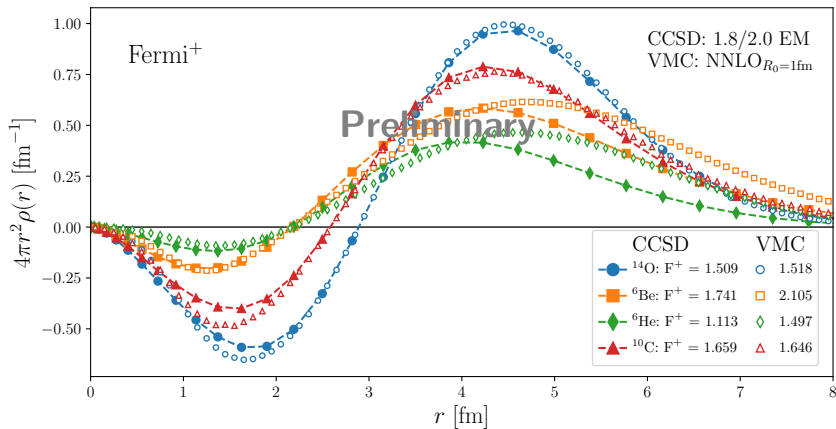
Qualitative agreement promising given different methods and interactions.



Regulation: $\delta(r) \propto e^{-r^4/R_0^4}$ vs. $f_\Lambda(r) \propto \int dk \, k^2 \, j_l(kr) f_\Lambda(k)$



$$\hat{O}_{\text{SO},p} = \tau_i^+ \hat{P}_j^p \left(-i \hat{r}_{ij} \times \left(\vec{\nabla}_i - \vec{\nabla}_j \right) \right) \cdot \vec{\sigma}_j + (i \leftrightarrow j)$$



$$\hat{O}_{\text{F}^+,p} = -\log(r/R_A) \left[\tau_i^+ \hat{P}_j^p + (i \leftrightarrow j) \right]$$

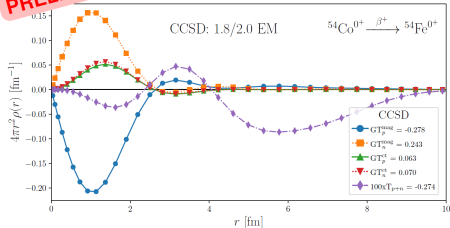
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Extracting V_{ud}

$$^{14}\text{O} \rightarrow ^{14}\text{N} : V_{ud} = 0.97364(10)_{\text{exp}}(12)_{\Delta_R^V}(22)_{\text{out}}(12)_{\delta_C}(43)_{\delta_{\text{NS}}^{\text{ct}}}(20)_{\delta_{\text{NS}}}$$

$$V_{ud} = 0.97364(56)_{\text{tot}}, V_{ud} = 0.97405(37)_{\text{tot}} (\text{Towner, Hardy})$$

PRELIMINARY



Transition	$M_{\text{GT}+\text{T},p}^{\text{mag}}$	$M_{\text{GT}+\text{T},n}^{\text{mag}}$	$M_{\text{GT},p}^{\text{CT}}$	$M_{\text{GT},n}^{\text{CT}}$
$^{10}\text{C} \rightarrow ^{10}\text{B}$	-0.327	0.082	0.044	0.027
$^{14}\text{O} \rightarrow ^{14}\text{N}$	-0.486	0.239	0.050	0.031
$^{26}\text{Al} \rightarrow ^{26}\text{Mg}$	-0.221	0.229	0.048	0.060
$^{34}\text{Cl} \rightarrow ^{34}\text{S}$	-0.368	0.305	0.047	0.056
$^{38}\text{K} \rightarrow ^{38}\text{Ar}$	-0.407	0.330	0.048	0.059
$^{42}\text{Sc} \rightarrow ^{42}\text{Ca}$	-0.229	0.218	0.053	0.062
$^{46}\text{V} \rightarrow ^{46}\text{Ti}$	-0.268	0.225	0.058	0.066
$^{50}\text{Mn} \rightarrow ^{50}\text{Cr}$	-0.270	0.231	0.060	0.067
$^{54}\text{Co} \rightarrow ^{54}\text{Fe}$	-0.273	0.235	0.062	0.070

Need consistent δ_C , Need uncertainty quantification, Need SO validation,
Fit contact terms to check accuracy and precision of V_{ud}

Summary and Outlook

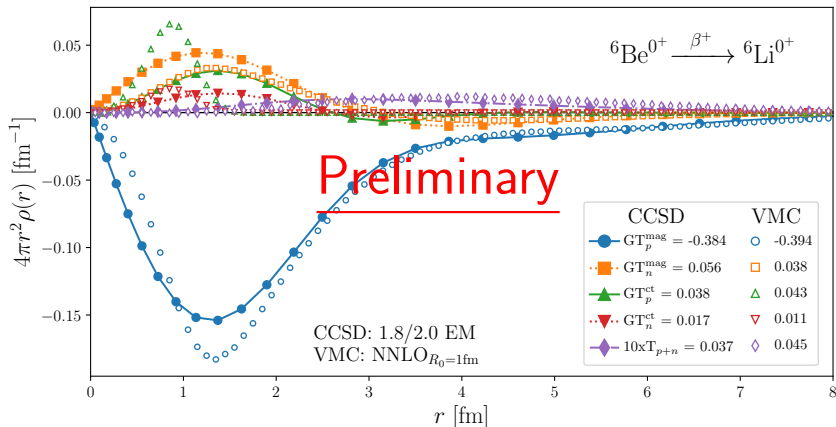
- Extended r-space EW operators to HO-space.
 - Computed EW transition densities for superallowed β -decays.
 - Expanded transition densities to CC and compared to VMC.
 - Utilized results to calculate δ_{NS} and $|V_{ud}|^2$.
-
- Calculate δ_{NS} for medium-mass superallowed candidates.
 - Study convergence, additional interactions and correlations.
 - Apply transition density machinery to $0\nu\beta\beta$ models.

Thank You!

- Garrett King (LANL)
- Saori Pastore (WUSTL)
- Maria Piarulli (WUSTL)
- Stefano Gandolfi (LANL)
- Emanuele Mereghetti (LANL)
- Vincenzo Cirigliano (INT)
- Wouter Dekens (INT)



Superaligned: ${}^6\text{Be} \rightarrow {}^6\text{Li}$



Superaligned: ${}^6\text{Li} \leftarrow {}^6\text{He}$

