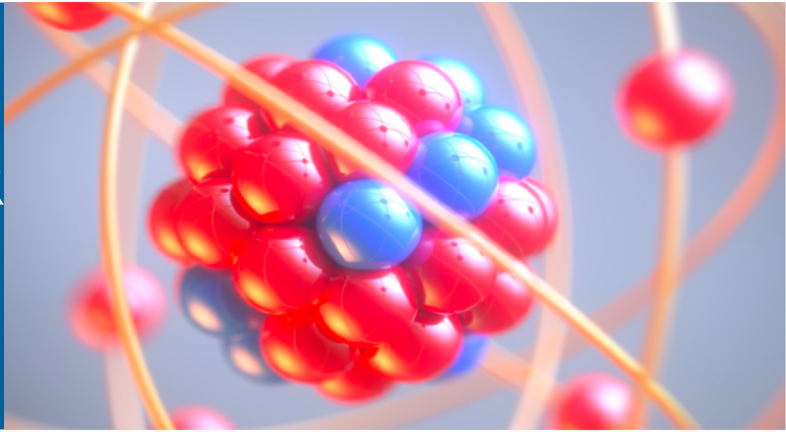
NEUTRINO-LESS DOUBLE-BETA DECAY: COMBINING QUANTUM MONTE CARLO AND THE NUCLEAR SHELL MODEL WITH THE GENERALIZED CONTACT FORMALISM



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Based on:
R. Weiss, P. Soriano, AL, J.Menendez, R.B. Wiringa,
ArXiv: 2112.08146 [nucl-th]

NSF PROJECT SCOPING WORKSHOP
"Towards Precise and Accurate Calculations of Neutrinoless Double-Beta Decay"

January 31 - February 1, 2022

THREE COMPLEMENTARY APPROACHES

- Variational Monte Method can accurately model the short- and long-range components of neutrino-less double beta decay transitions, but it is limited to light nuclei;
- The generalized contact formalism captures short-range nuclear dynamics of *all* nuclei, but does not provide information on their long-range structure;
- The shell-model is suitable to accurately model long-range properties of many nuclei fat fail to properly describe short-range nuclear dynamics;

We combine them to compute $0\nu\beta\beta$ the matrix elements of nuclei ^{48}Ca, ^{76}Ge, ^{130}Te, and ^{136}Xe.

$$M^{0\nu} = \langle\Psi_f|O^{0\nu}|\Psi_i\rangle$$

We consider the "conventional" long-range transitions plus the recently identified short-range term

$$O_F^{0\nu} = (4\pi R_A)\sum_{a\neq b} V_F^{0\nu}(r_{ab})\tau_a^+\tau_b^+\,,$$

$$O_{GT}^{0\nu} = (4\pi R_A)\sum_{a\neq b} V_{GT}^{0\nu}(r_{ab})\,\sigma_{ab}\,\tau_a^+\tau_b^+$$

$$O_T^{0\nu} = (4\pi R_A)\sum_{a\neq b} V_T^{0\nu}(r_{ab})S_{ab}\,\tau_a^+\tau_b^+$$

$$O_S^{0\nu} = (4\pi R_A)\sum_{a\neq b} V_S^{0\nu}(r_{ab})\tau_a^+\tau_b^+$$

BRIEF DESCRIPTION OF THE GCF-SM METHOD

When two particles are close to each other, any nuclear wave function obeys the asymptotic form

$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_{\alpha} \varphi^{\alpha}(\boldsymbol{r}_{ij}) A^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j}) \quad \longleftrightarrow \quad \varphi^{\alpha}(\boldsymbol{r}) \equiv \eta_{t_\alpha, t_{\alpha z}} \sum_{\ell_\alpha \in \pi_\alpha} \phi^{\alpha}(r) \left[Y_{\ell_\alpha}(\hat{\boldsymbol{r}}) \otimes \chi_{s_\alpha} \right]^{j_\alpha m_\alpha}$$

The nuclear contacts for transitions that involve different initial and final states are defined as

$$C^{\alpha\beta}(f,i) = \frac{A(A-1)}{2} \langle A^{\alpha}(f) | A^{\beta}(i) \rangle$$

The dominant contributions to the Fermi and Gamow-Teller transition densities are given by

$$\rho_F(r) \xrightarrow[r\to 0]{} \frac{1}{4\pi} |\phi^0(r)|^2 C^0_{pp,nn}(f,i) \quad ; \quad \rho_{GT}(r) \xrightarrow[r\to 0]{} -\frac{3}{4\pi} |\phi^0(r)|^2 C^0_{pp,nn}(f,i)$$

The contacts are typically determined on VMC calculations, which are not feasible for heavy nuclei.

VALIDATION OF THE GCF-SM METHOD

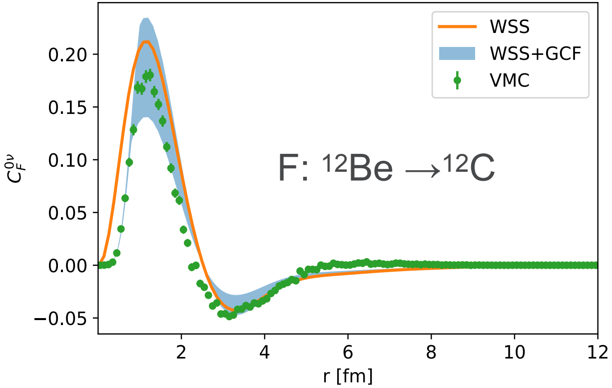
The ratio of contacts is a low-resolution quantity that should not depend on the nuclear interaction

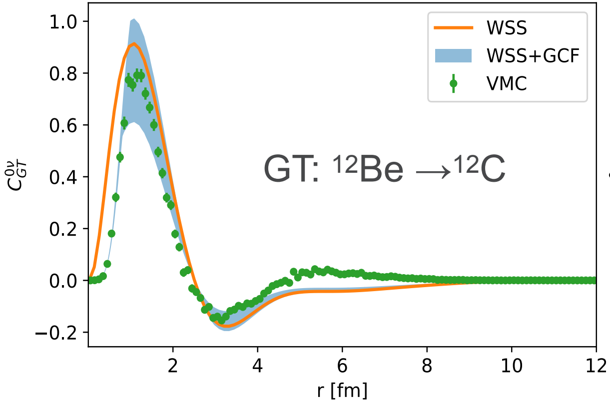
$$C^{0,V_N}_{pp,nn}(f_1,i_1) = \frac{C^{0,\mathrm{SM}}_{pp,nn}(f_1,i_1)}{C^{0,\mathrm{SM}}_{pp,nn}(f_2,i_2)} C^{0,V_N}_{pp,nn}(f_2,i_2)$$

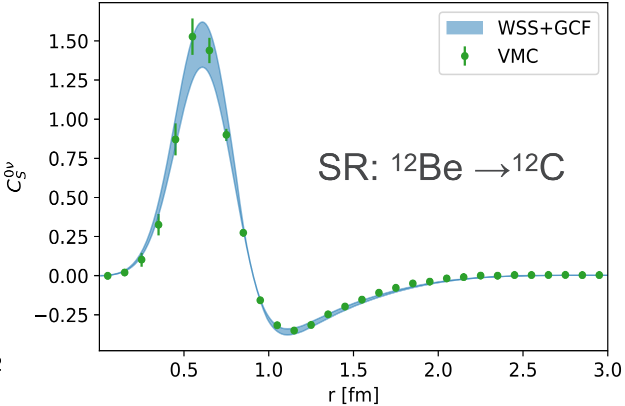
- $i_1 \to f_1$ heavy-nucleus transition
- $i_2 \to f_2$ light-nucleus transition

We merge the GCF and SM densities by scaling the latter to match the GCF expression at r ≃ 1 fm

We teste this assumptions on VMC transition densities: ^{12}Be →^{12}C, ^{10}Be →^{10}C, and ^{6}He →^{6}Be

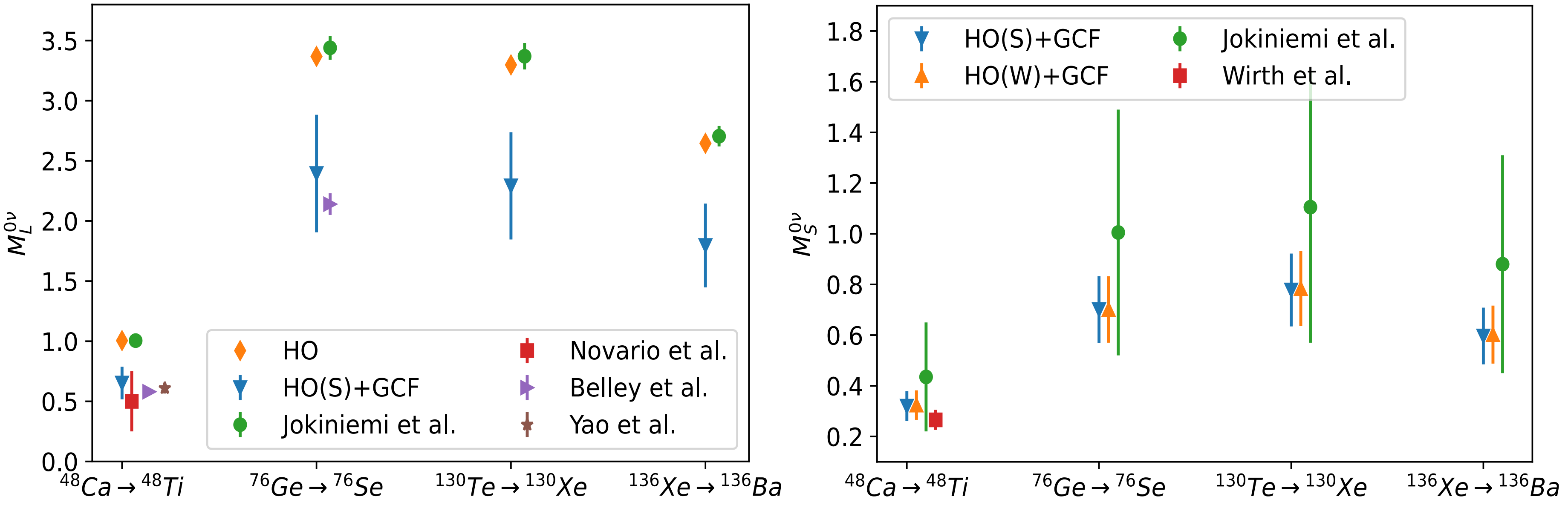






PREDICTIONS OF THE GCF-SM

Having validated the GCF-SM on light nuclei, we make prediction for heavy emitters, comparing with other approaches



Good agreement with microscopic approaches for ^{48}Ca and ^{76}Ge, results for ^{130}Te and ^{136}Xe indicate 20% quenching with respect to SM results;

PATH FORWARD (MODEL UNCERTAINTY)

So far we used the highly-realistic but phenomenological AV18 + UIX Hamiltonian

- Extension to local chiral-EFT interactions straightforward within the VMC
- Using non-local chiral-EFT interactions is also possible, but requires ab-initio methods other than the VMC, e.g. the no-core shell model

Thorough test of the model-independence of the ratios:

- Comparing with other microscopic approaches (CC, IM-SRG, etc.);
- Complementary theoretical insight from the operator evolution from the similarity renormalization group

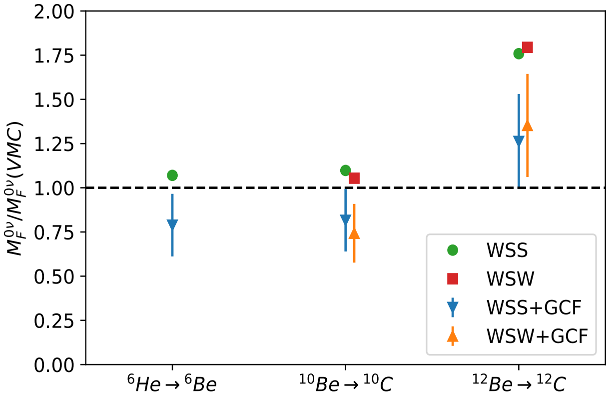
Extending the GCF-SM approach

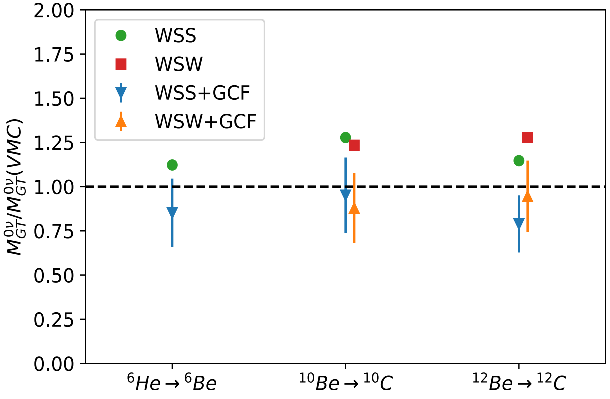
- Go beyond the two-nucleon factorization including three-body effects
- Computing other quantities, including neutrino-full single- and double-beta decays

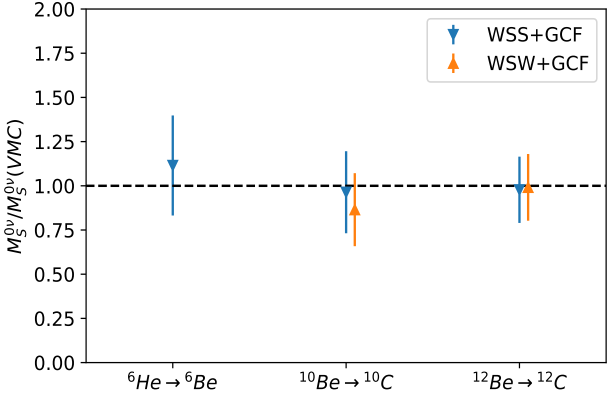
BACKUP SLIDES

PATH FORWARD (MODEL UNCERTAINTY)

Comparison with VMC matrix elements of light nuclei







Harmonic-Oscillator vs Wood-Saxon orbitals

- Major differences in light nuclei
- Almost no differences in heavy nuclei