Weak Interaction Theory for Heavy Nuclei

Considerations for Neutrinoless Double Beta Decay

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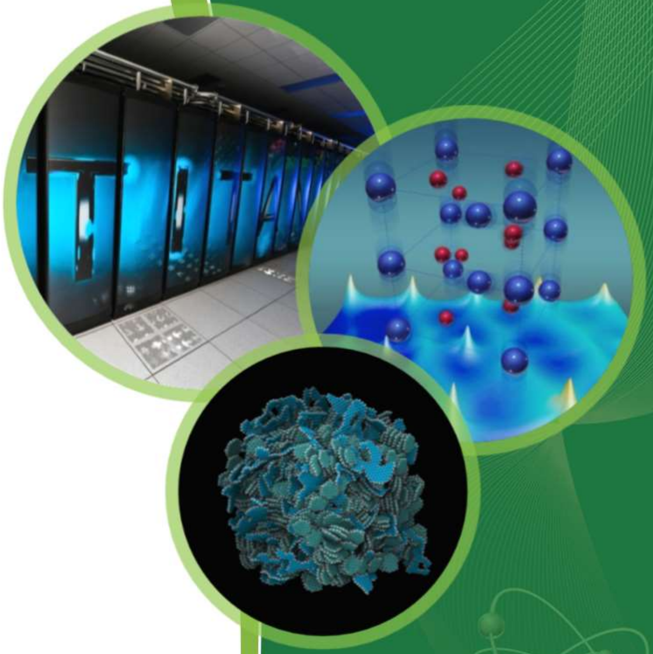

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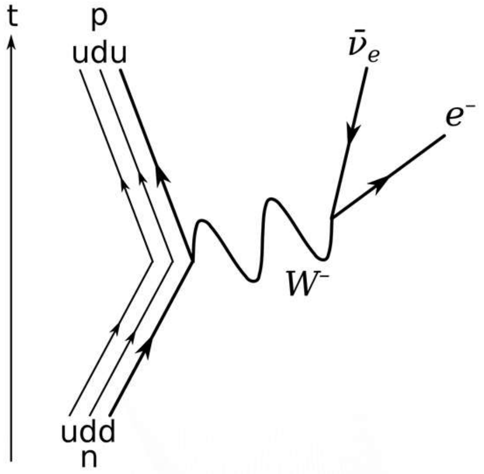
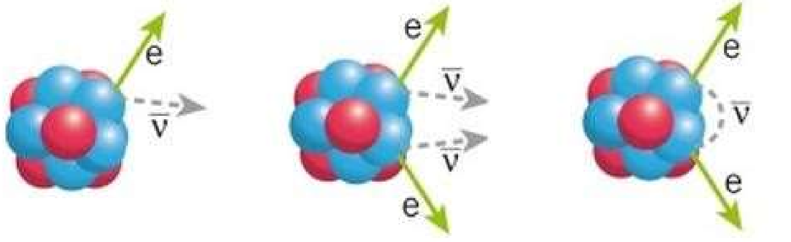
Weak interaction primer

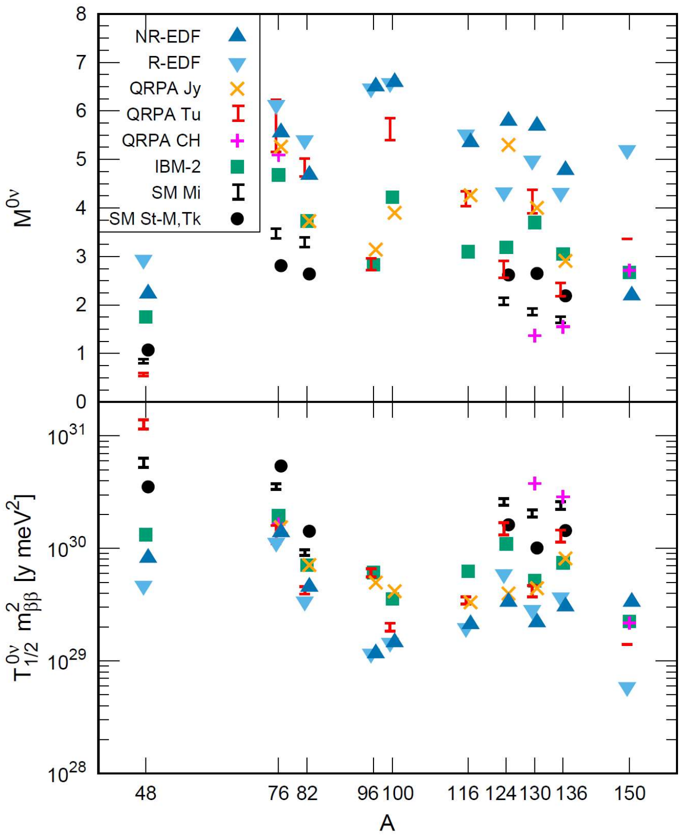
- Changes quark flavor.
  - Break parity and charge parity symmetry.
  - Breaks conservation of lepton number.
  - Responsible for beta decays.
- Changes neutron into a proton and vice versa.
  - Effective operators from field theory
  - Calculate decay rates in nuclei by calculating expectation values between many-body wave functions.





Standard β decay | Double-β decay | Neutrino-less double-β decay

The Nuclear Matrix Element (NME) for $0\nu\beta\beta$

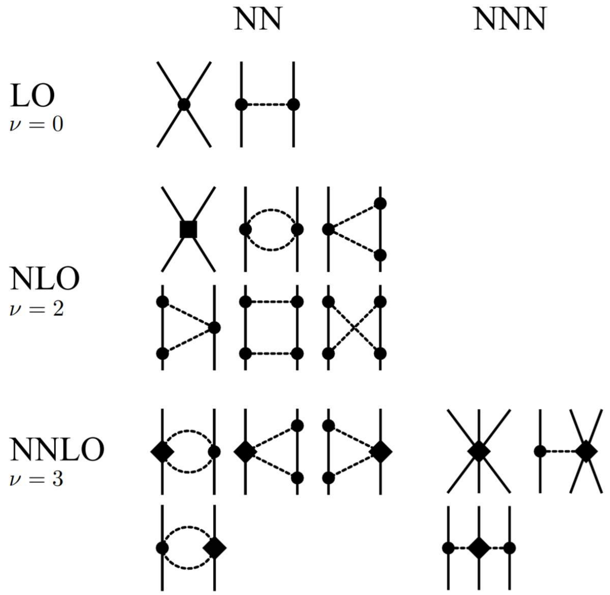


Jonathan Engel, Javier Menendez, *Status and Future of Nuclear Matrix Elements for Neutrinoless Double-Beta Decay: A Review*, **Reports on Progress in Physics, 80, 4, 2017**.

- Decay rate is proportional to $|M^{0\nu}|^2$ and $m^2_{\beta\beta}$.
- Models differ by a factor of 3-5.
- No rigorous uncertainty quantification possible.
- All models need a phenomenological quenching factor to get beta decay right.

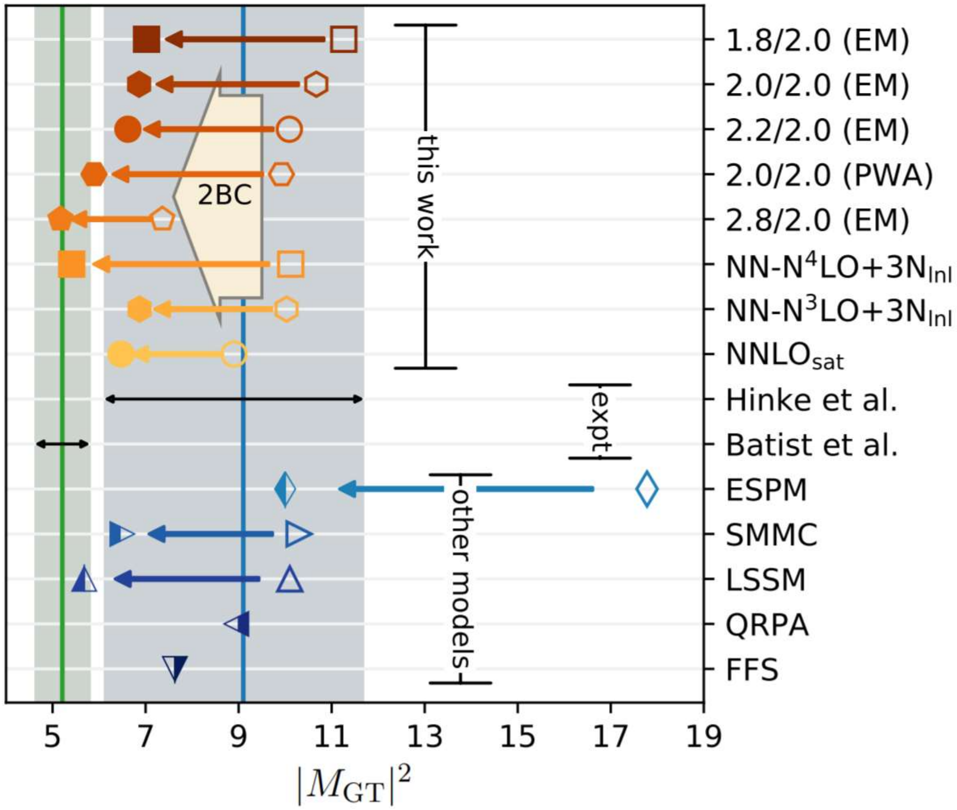
Chiral effective field theory (χEFT)

- Currently considered the best framework for obtaining effective interactions between nucleons.
- Preserves the symmetries from QCD.
- Effective theory expanded around a momentum scale.
- Low-energy constants fitted to experimental data.
- Couples to weak currents for consistent derivation of interactions and weak transition operators.



Weak transitions from ab-initio theory

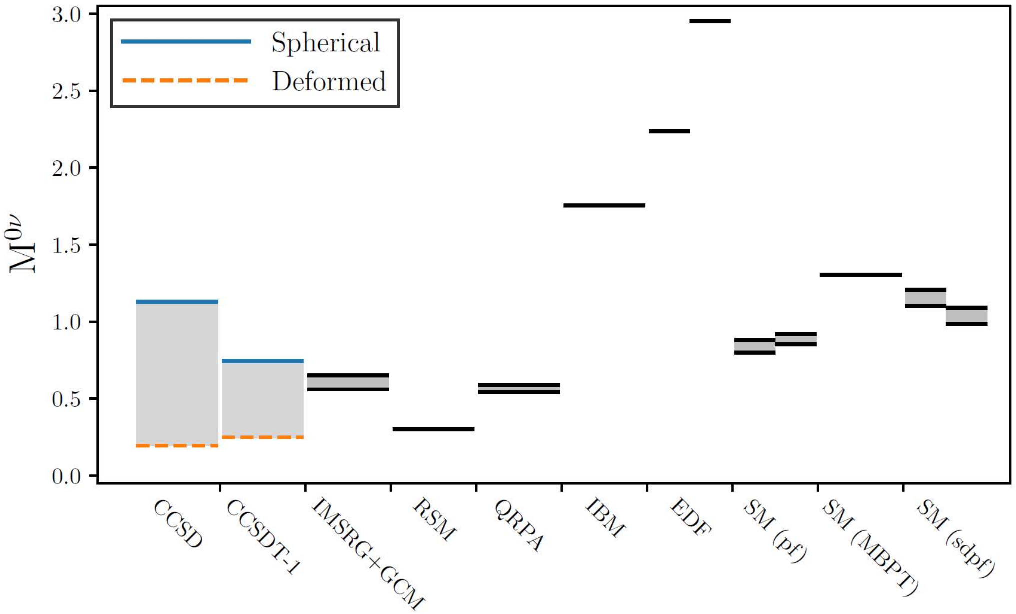
- Dominant beta decay (Gamow Teller) of the groundstate of ^{100}Sn to ^{100}In.
  - Strongest of all measured GT transitions.
- Uses interactions from χEFT with different momentum cutoffs.
  - Includes three-body forces, but not consistently.
- Uses up to two-body currents to obtain the GT operator.
  - At zero momentum transfer.
- Calculations performed on Summit using the NuCCOR code (CCSDT-1).



Gysbers et al., *Discrepancy between experimental and theoretical β-decay rates resolved from first principles*, **Nature Physics, 15, 428, 2019**.

$0\nu\beta\beta$ of ^{48}Ca from coupled-cluster theory

- Calcium-48 is the ideal case for coupled-cluster theory.
  - Doubly-magic and spherical.
  - Titanium-48 is accessible in a spherical formalism.
- A spherical formalism was not sufficient.
  - Titantium-48 is deformed, but axially symmetric.
  - Several orders of magnitude more expensive to compute.
  - Unknown effects of breaking rotational symmetry.
- Ab-initio results are coming in very low.
  - Points to higher lifetimes and lower decay rate



Novario et al., *Coupled-cluster calculations of neutrinoless double-beta decay in 48Ca,* **Phys. Rev. Lett. 126, 182502, 2020**.

Challenge I: Uncertainty quantification

- Sources of uncertainty.
  - Choice of χEFT (pion-less, delta-less, delta-full, …).
  - Low-energy constants in χEFT.
  - Approximation of wave function.
  - Solution to the Schrödinger equation.
  - Numerical approximations.
- More computational resources?
- Can we use new AI/ML tools?
- Theoretical error bounds from solving the Schrödinger equation?

Challenge II: Chiral effective field theory

- No obvious order-by-order convergence or cutoff independence.
  - Is the power-counting scheme wrong?
- Current interactions are not suitable for heavier nuclei.
  - Strong tendency to only include few-body data to determine low-energy constants.
- Contact term for $0\nu\beta\beta$ decay with unknown strength.
  - No known experiment can fix the low-energy constant for this term.
  - Can the strength be determined from LQCD?

Challenge III: Deformation

- Most of the nuclei relevant for $0\nu\beta\beta$ decay are deformed.
  - Need higher order many-body methods to capture deformation
    - Tri-axial deformation is important as well.
  - Symmetries of the Hamiltonian must be broken.
    - Leads to larger basis sets and more complicated wave functions.
  - Broken symmetries must be restored for accurate evaluation of expectation values.
    - We are only now figuring out how this can be done for rotational symmetry, and it is expensive.

Thank you!