Nuclear Observables as Probes of Neutrinoless Double-Beta Decay

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Introduction

Observing neutrinoless double-beta decay would be the most feasible way to shed light on the matter-antimatter asymmetry of the Universe and the nature of the neutrino. However, in order to interpret the experiments, reliable theory estimates are called for. The estimates can be constrained by related nuclear observables.

Double-Beta Decay

Double-beta ($\beta\beta$) decay is a weak interaction process in which two neutrons inside an atomic nucleus transform into protons and two electrons are emitted. There are two modes of the decay:

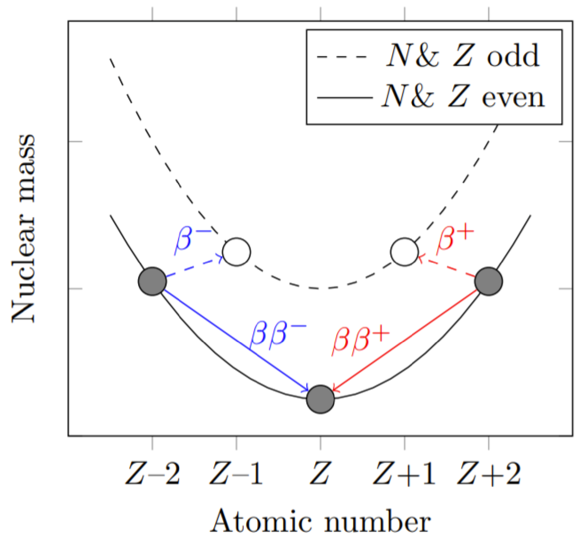

Figure 1: $\beta\beta$ decay is possible when β decays are energetically forbidden.

- **Two-neutrino double-beta ($2\nu\beta\beta$) decay**
  - observed in ~10 nuclei
  - $t_{1/2}^{2\nu} \approx 10^{20}$ y
- **Neutrinoless double-beta ($0\nu\beta\beta$) decay**
  - Requires that neutrino is Majorana particle
  - Violates lepton-number conservation
  - $t_{1/2}^{0\nu} \gtrsim 10^{25}$ y

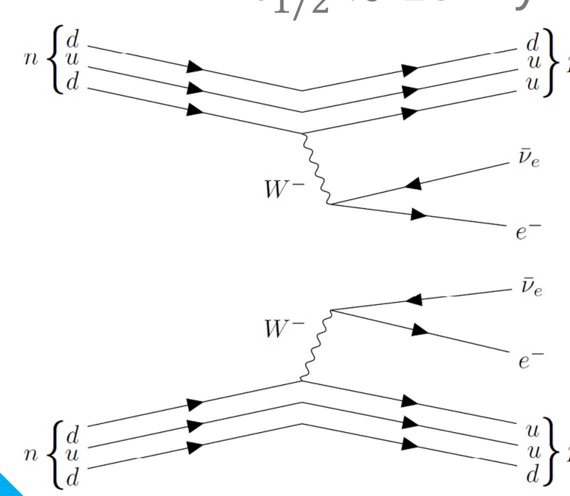

Figure 2: $2\nu\beta\beta$decay.

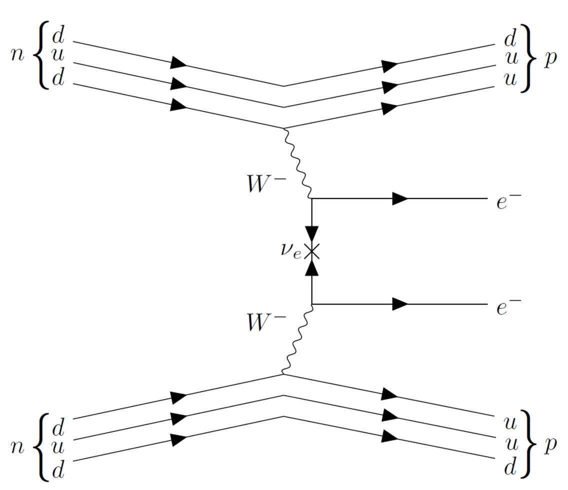

Figure 3: $0\nu\beta\beta$decay.

Half-Life of $0\nu\beta\beta$-decay

Assuming $0\nu\beta\beta$ decay is mediated by light-neutrino exchange, the half-life can be written as:

$$\frac{1}{t_{1/2}^{0\nu}} = G_{0\nu} g_A^4 |M_L^{0\nu} + M_S^{0\nu}| \frac{m_{\beta\beta}^2}{m_e^2}$$

where

- $G_{0\nu}$: phase-space factor
- g_A: axial-vector coupling constant
  - **Quenched or not?**
- $M_L^{0\nu}, M_S^{0\nu}$: long- and short-range nuclear matrix elements (NMEs)
  - **Uncertain theory estimates**
- $m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3$: effective neutrino mass

Reliable theory estimates crucial to interpret experiments - how could other nuclear observables help constrain them?

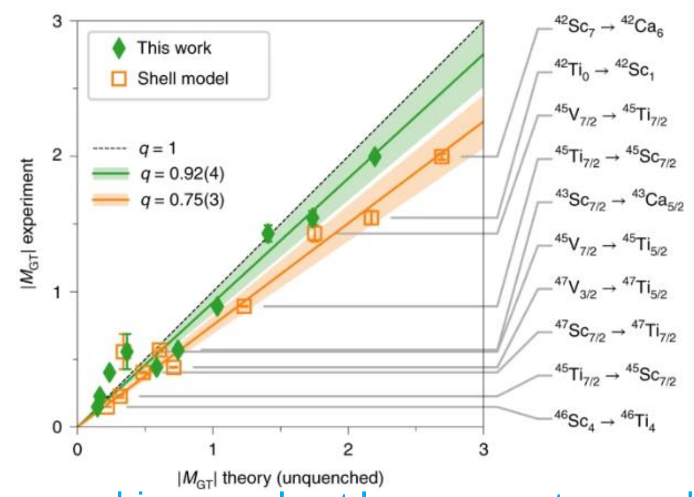

Figure 3: g_A quenching puzzle at low momentum exchange solved from first principles. [*Nat Phys.* **15**, 428 (2019)]

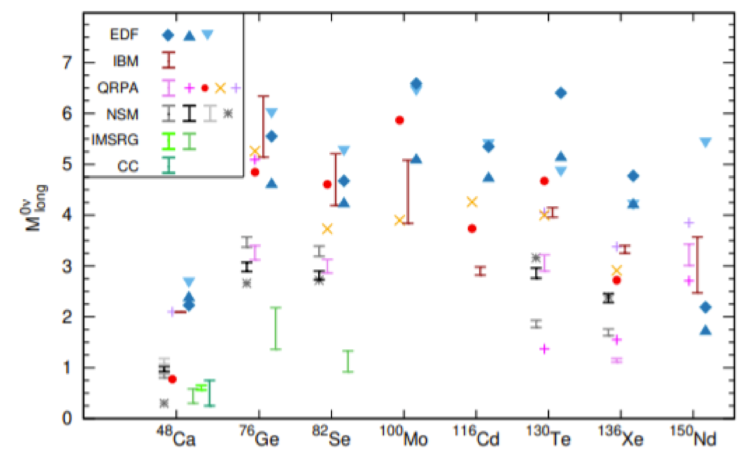

Figure 4: NMEs from different models. [arXiv:2202.01787]

Acknowledgements

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Probe 1: Two-Neutrino Double-Beta Decay

Analogy between $0\nu\beta\beta$ and $2\nu\beta\beta$ decays:

- **Same initial and final states**
- Different momentum exchange: $q_{0\nu\beta\beta} \approx 100$ MeV, $q_{2\nu\beta\beta} \approx 0$ MeV
- Different intermediate states (only 1^+ for $2\nu\beta\beta$, all J^π for $0\nu\beta\beta$)

Correlation between $2\nu\beta\beta$ and $0\nu\beta\beta$ decays

+ measured $2\nu\beta\beta$-decay half-lives

→ estimates for $0\nu\beta\beta$-decay NMEs

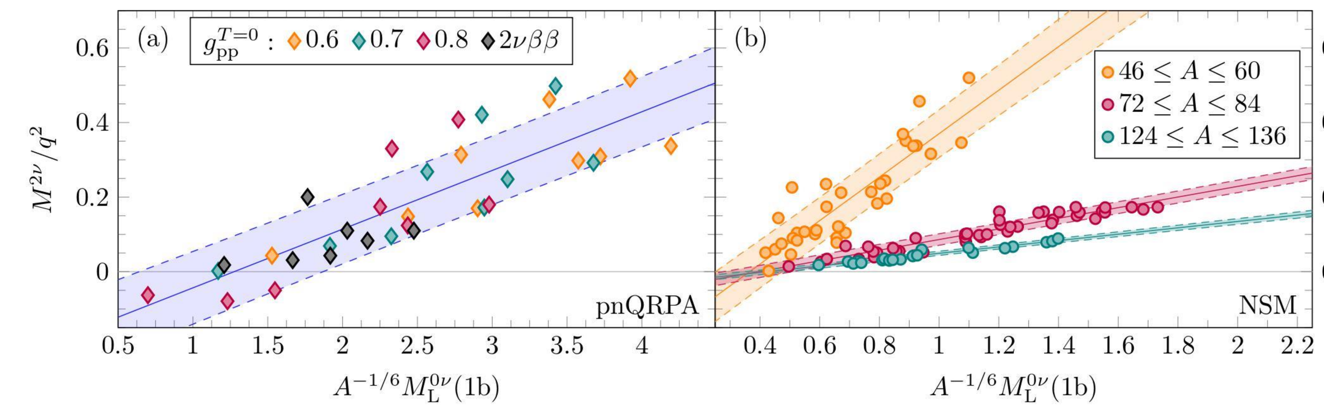


Figure 5: Correlation between $2\nu\beta\beta$- and $0\nu\beta\beta$-decay NMEs observed in nuclear shell model and pnQRPA [arXiv:2207.05108].

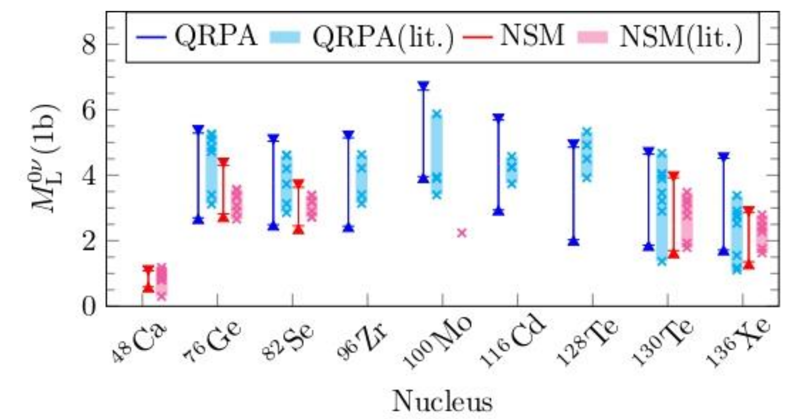
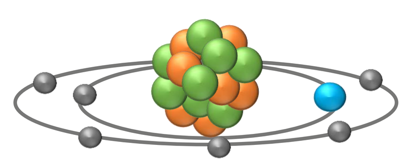


Figure 6: $0\nu\beta\beta$-decay NMEs extracted from the $2\nu\beta\beta$-$0\nu\beta\beta$ correlation [arXiv:2207.05108].

Probe 2: Ordinary Muon Capture (OMC)

$$(A,Z) + \mu^- \to (A, Z-1) + \nu_\mu$$



Analogy between $0\nu\beta\beta$ decay and muon capture:

- **Both involve momentum exchange $q \approx 100$ MeV**
- **OMC can excite states with all J^π values up to high energy** (can probe intermediate states of $0\nu\beta\beta$ decay)
- Different initial / final states

How to use muon capture as a probe of $0\nu\beta\beta$ decay?

- Phenomenological studies on total capture rates
  - **→ fix the model parameters**
- Ab initio studies on partial capture rates
  - **→ solve g_A quenching at $q \approx 100$ MeV**

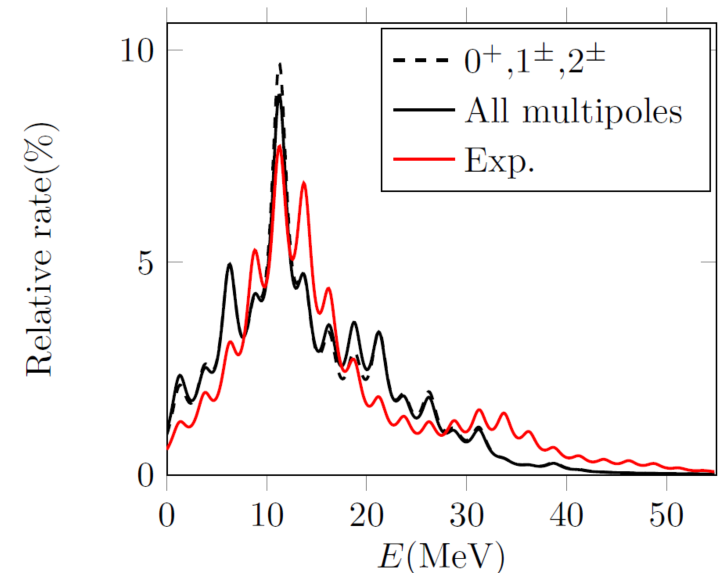


Figure 7: Muon-capture strength function in ^{100}Nb obtained in pnQRPA [*Phys. Lett. B*, **794**, 143 (2019)].

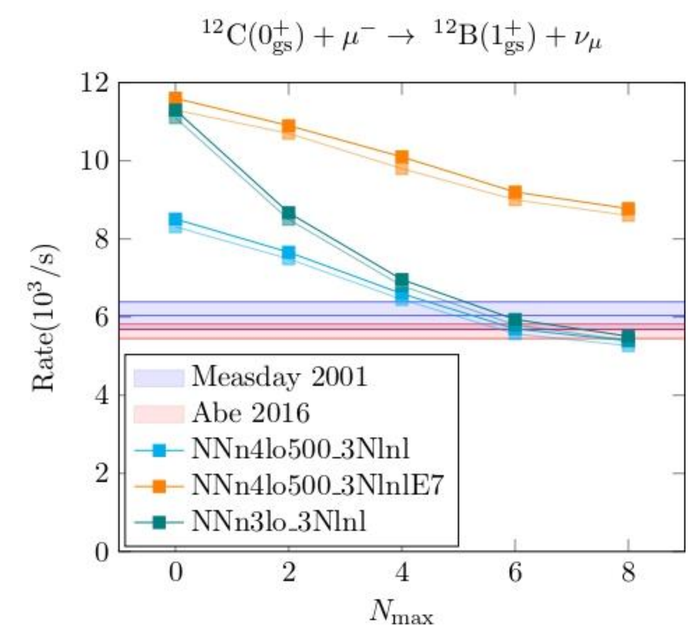


Figure 8: Partial muon-capture rates to the ground state of ^{12}B obtained in no-core shell model.

SUMMARY

Nuclear observables can help test the validity of the nuclear many-body methods and constrain the values of the poorly known $0\nu\beta\beta$-decay nuclear matrix elements. Particularly, ordinary muon capture and $2\nu\beta\beta$ decay can help probe $0\nu\beta\beta$ decay owing to the similarities of the processes.

Discovery, accelerated