Ab Initio Correlation between Double Gamow-Teller Transitions and Neutrinoless Double Beta Decay

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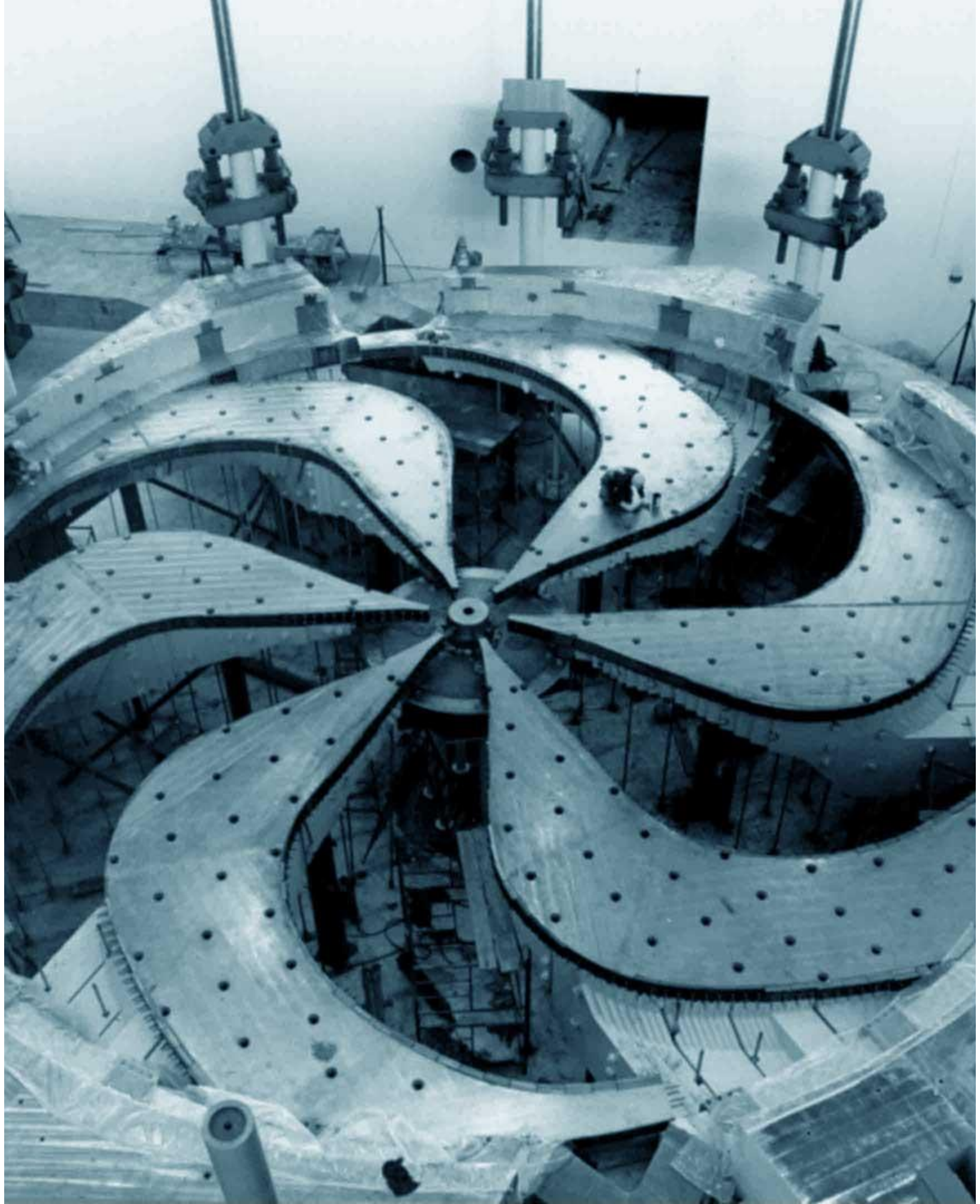
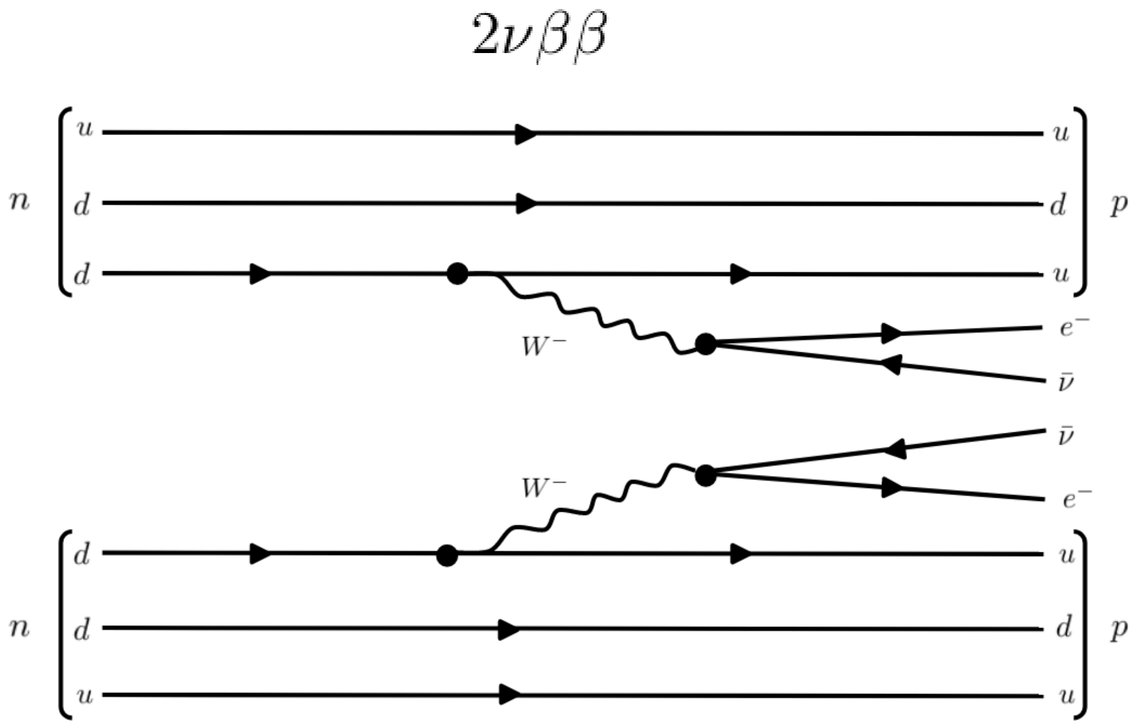
Summer Research Student, Theory Department

23 August 2021



Discovery, accelerated

What is 0νββ decay?



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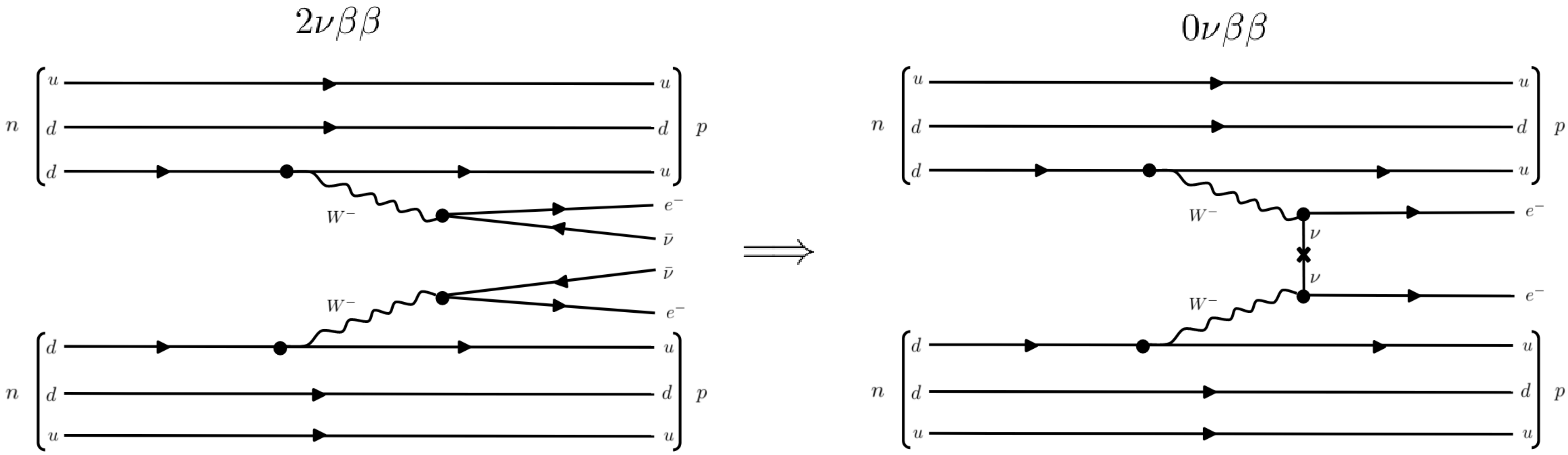
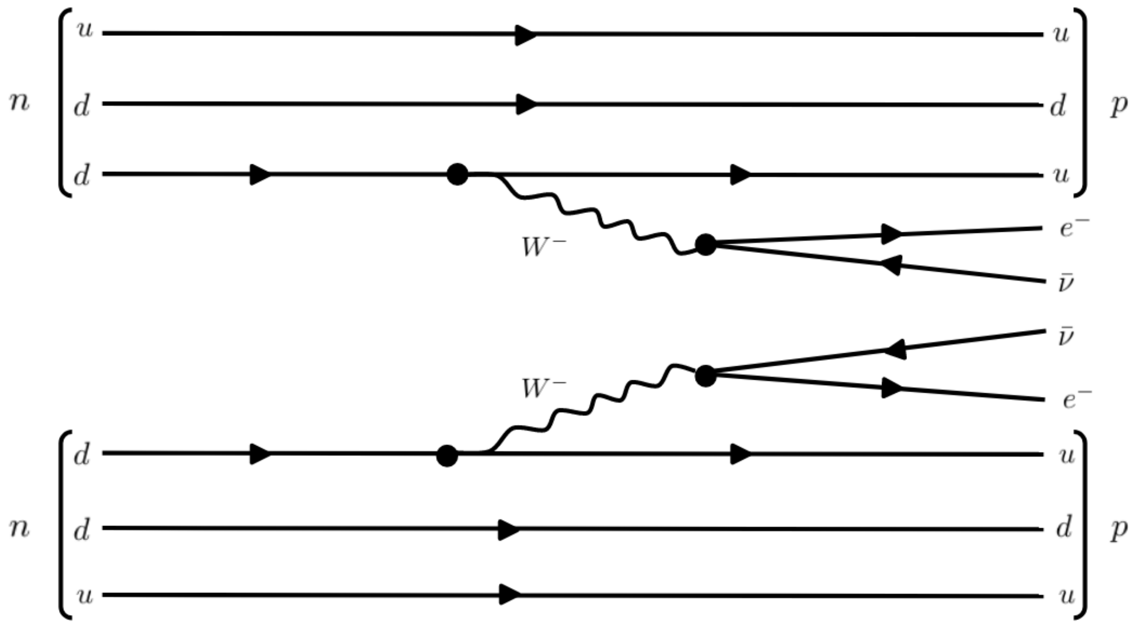


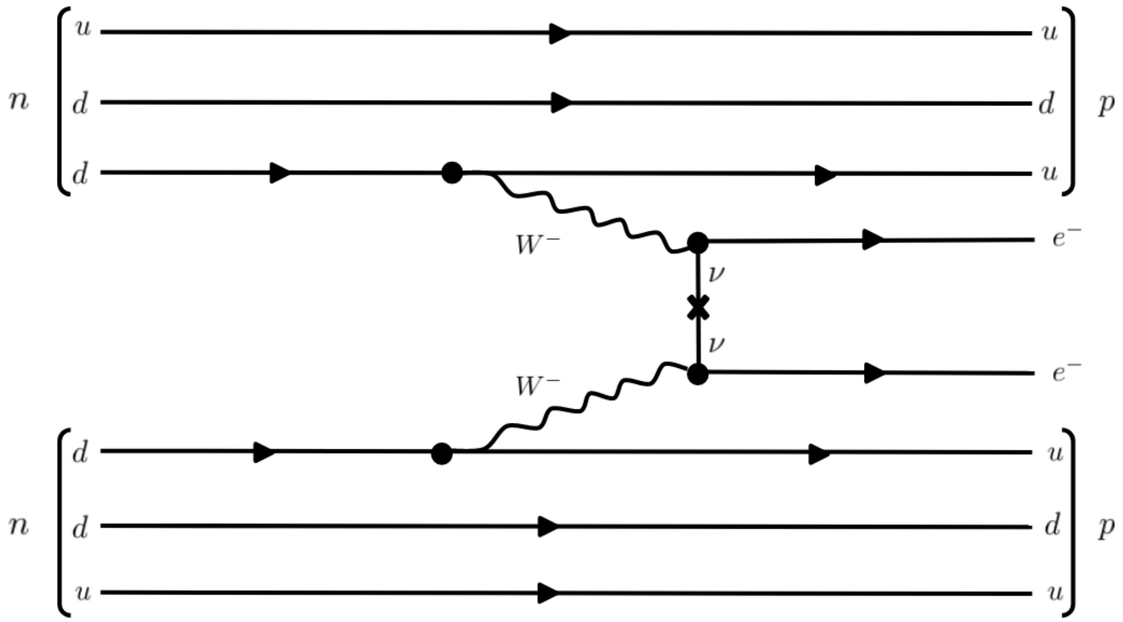
What is 0νββ decay?

$2\nu\beta\beta$



$\Longrightarrow$

$0\nu\beta\beta$



Allowed by the current Standard Model

2 neutrinos in the final state

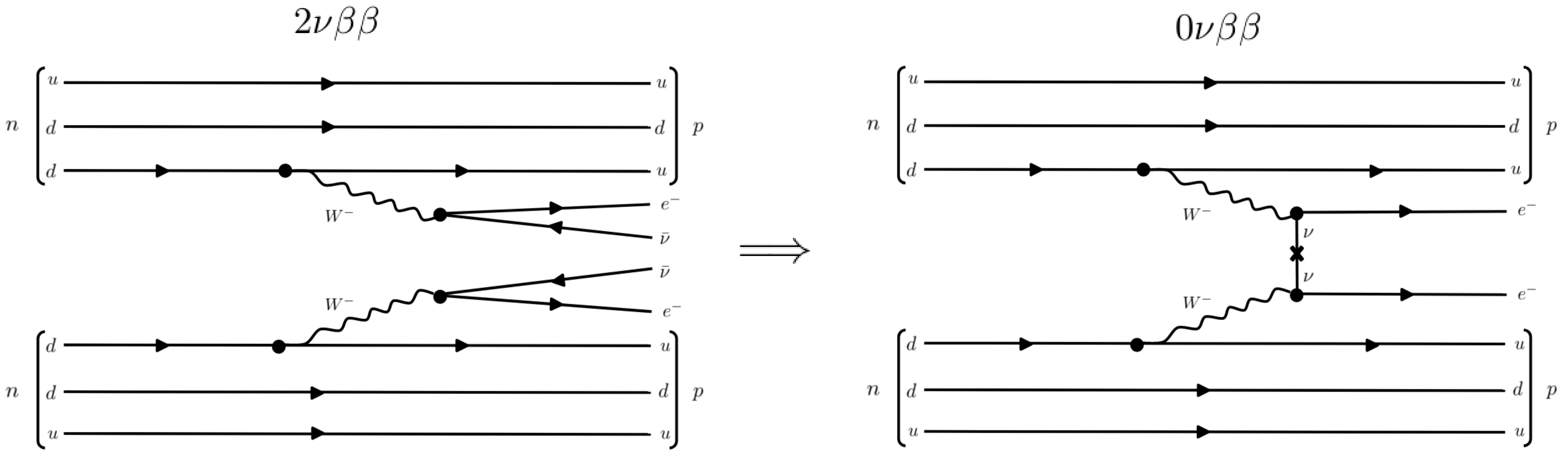
Neutrino is a Dirac fermion, i.e. particle and antiparticle are distinct

Beyond-Standard-Model (BSM) process

0 neutrinos in the final state

Neutrino is a Majorana fermion, i.e. its own antiparticle

What is $0\nu\beta\beta$ decay?



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Beyond-Standard-Model (BSM) process

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Neutrino is a Majorana fermion, i.e. its own antiparticle

Big impact on our understanding of BSM physics!

0νββ Half-Life Formula

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}|M^{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

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0νββ half-life

0νββ phase factor

Effective neutrino mass

$$\langle m_{\beta\beta}\rangle = \left|\sum_{k=1}^{3} m_k U_{ek}^2\right|$$

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0νββ half-life

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0νββ nuclear matrix element (NME)

This is where nuclear theory is important!

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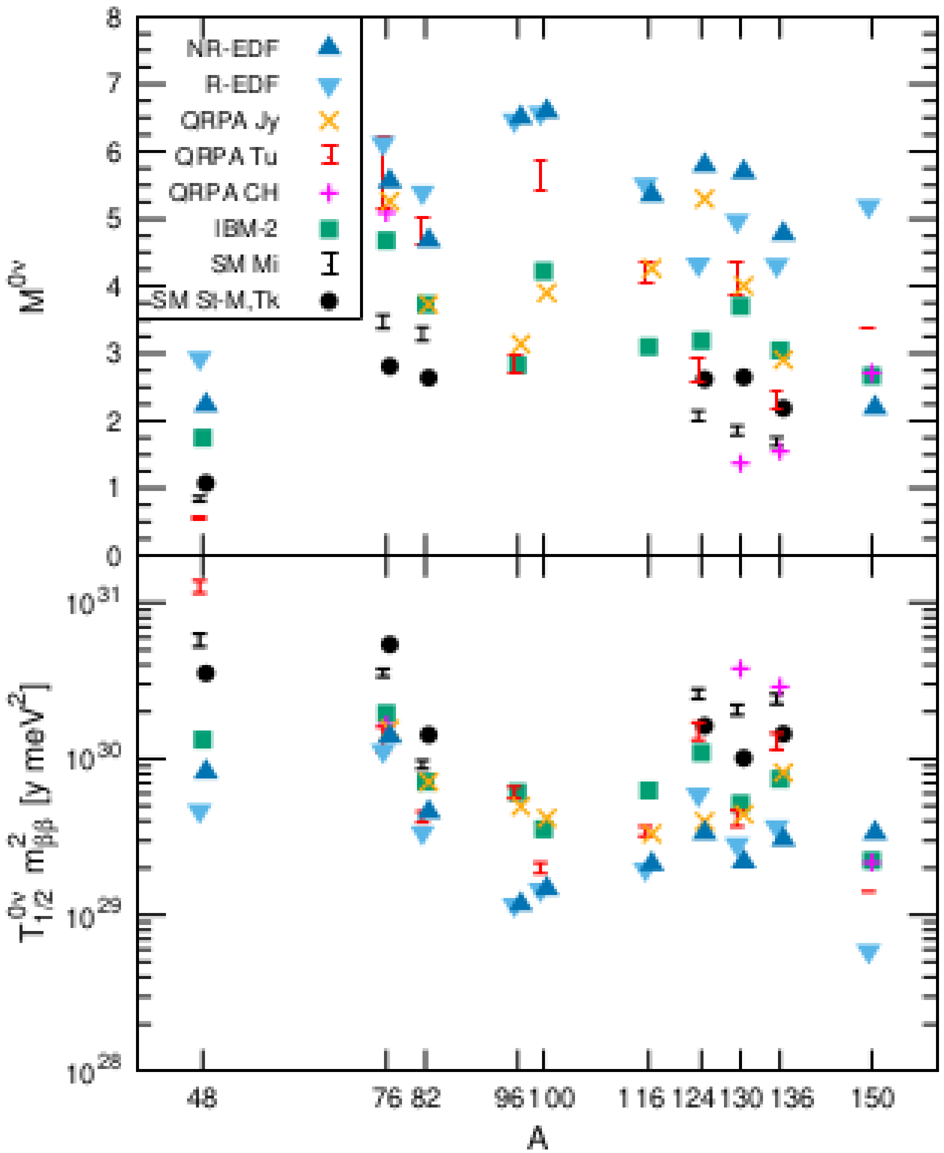
Current Progress in 0νββ Matrix Elements



J. Menéndez and J. Engel, Rep. Prog. Phys. **80**, 046301 (2017).

There is still a large spread in calculated 0νββ nuclear matrix elements.

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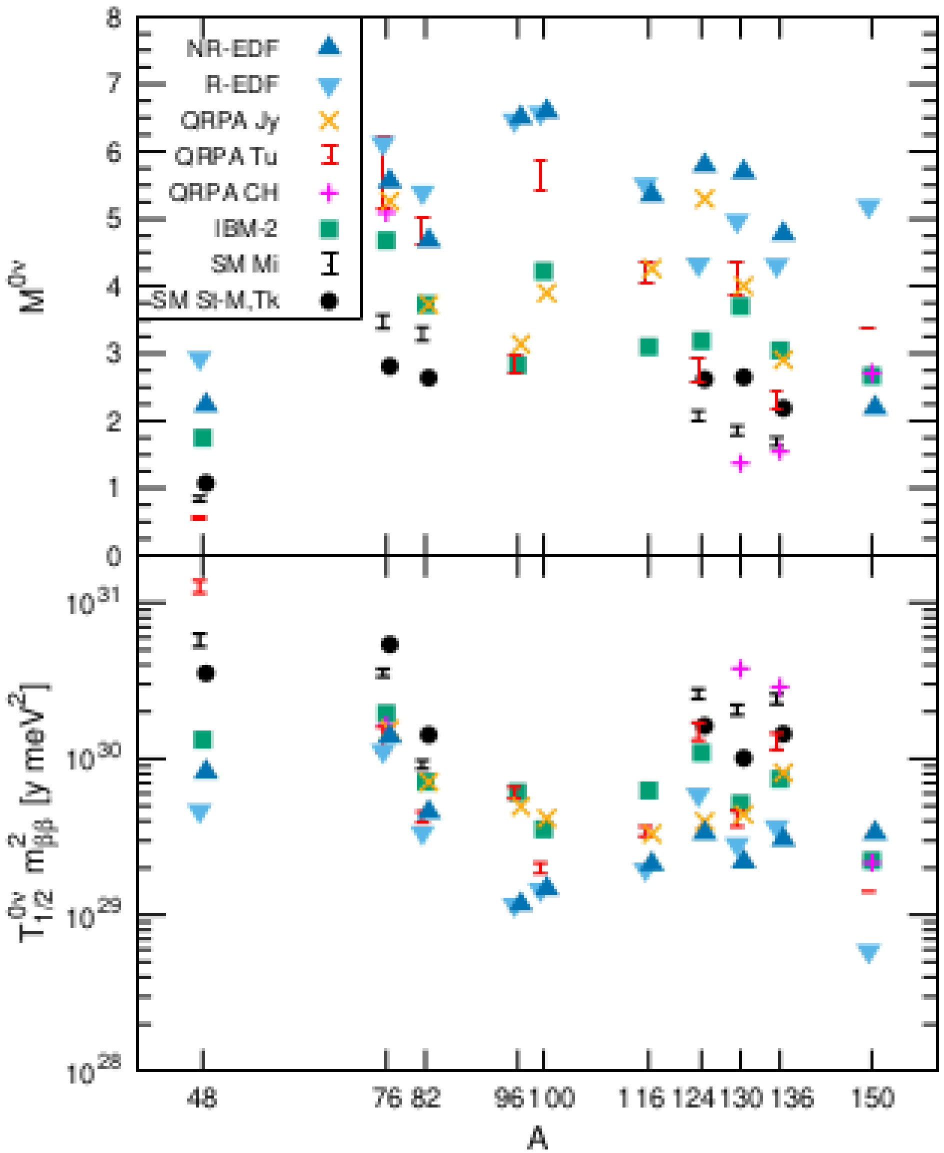

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There is still a large spread in calculated 0νββ nuclear matrix elements.

<u>Question</u>: what can be done to reduce NME uncertainties?

The Double Gamow-Teller Transition Operator

$$M^{DGT} = \langle 0^+_{gs,f} | \sum_{j,k} [\boldsymbol{\sigma}_j \tau^-_j \otimes \boldsymbol{\sigma}_k \tau^-_k]^0 | 0^+_{gs,i} \rangle$$

- Gamow-Teller (GT) transition: neutron changes to proton and the spin from neutron to proton flips
- Double Gamow-Teller (DGT) transition: a strong nuclear process where two neutrons change to two protons with the same spin flipping behavior

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$$M^{0\nu} = M^{0\nu}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_F + M^{0\nu}_T$$

$$M^{0\nu}_{GT} = \langle 0^+_{gs,f} | \sum_{j,k} [\boldsymbol{\sigma}_j \tau_j^- \otimes \boldsymbol{\sigma}_k \tau_k^-]^0 V_{GT}(r_{jk}) | 0^+_{gs,i} \rangle$$

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$$V_{GT}(r_{jk}) \approx \frac{1}{r_{jk}}$$

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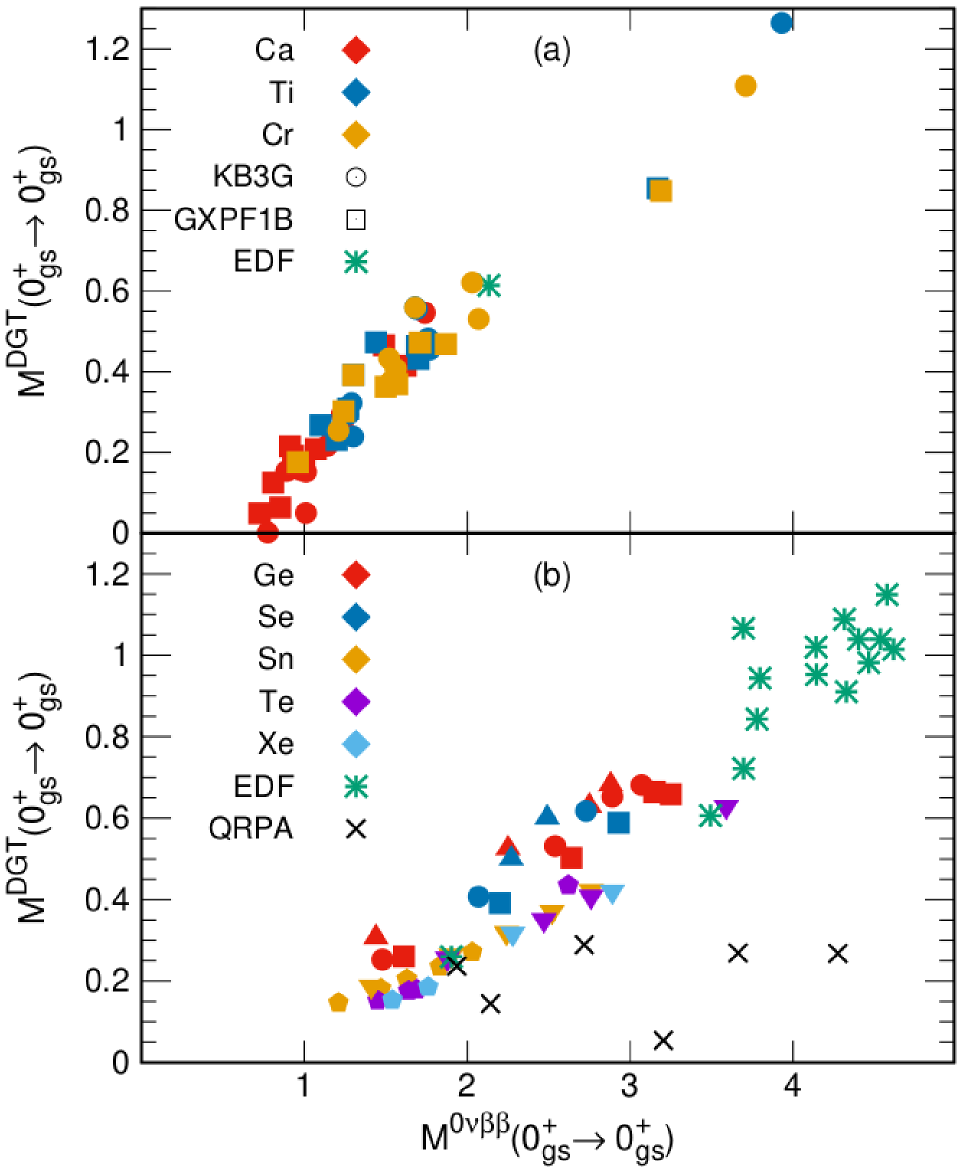
Only difference is the neutrino potential!

DGT Transition and 0νββ Decay Correlation



N. Shimizu et al. demonstrated that there is a linear correlation between double Gamow-Teller (DGT) transition NMEs and 0νββ decay NMEs using phenomenological techniques.

N. Shimizu et al., Phys. Rev. Lett. **120**, 142502 (2018).

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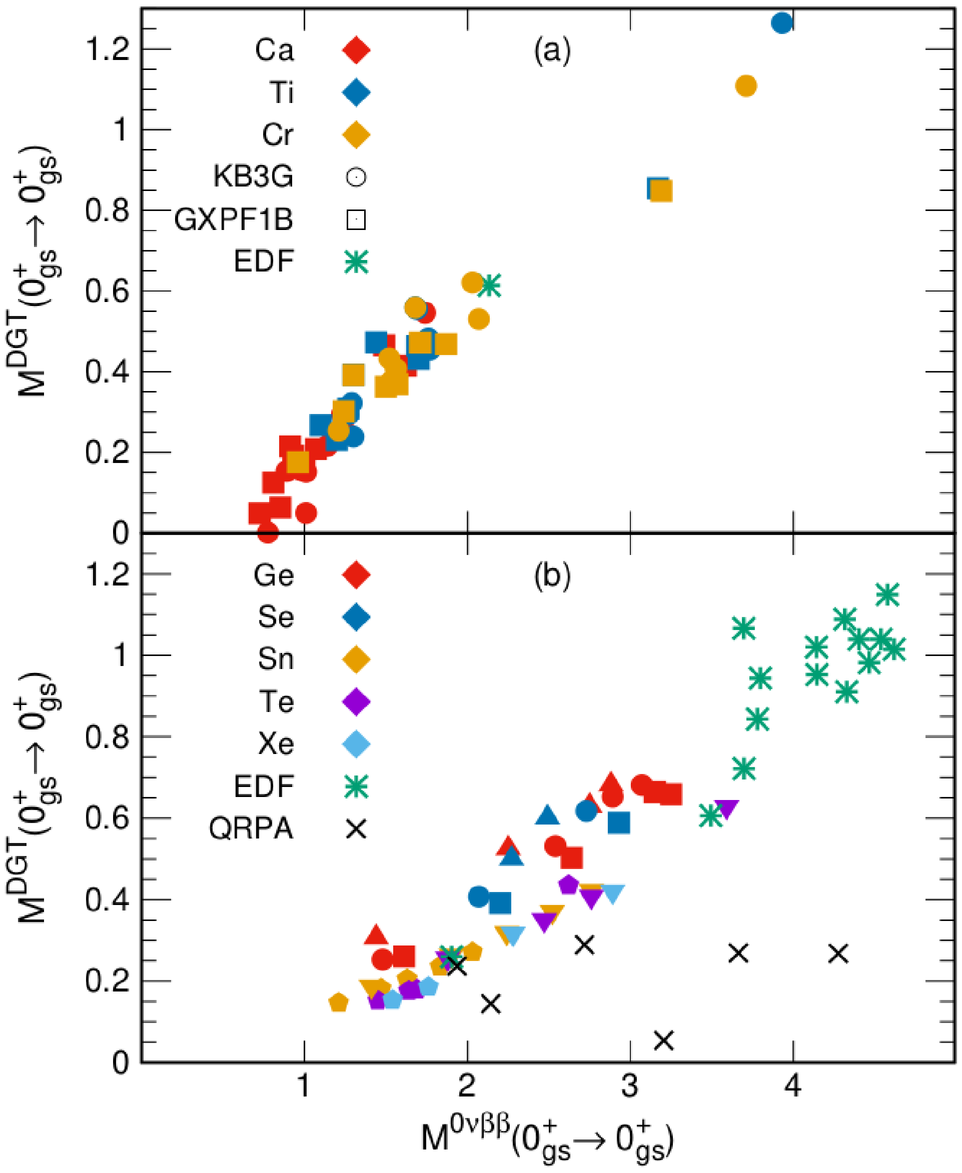

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Question: does this correlation hold when using first principles computational methods?

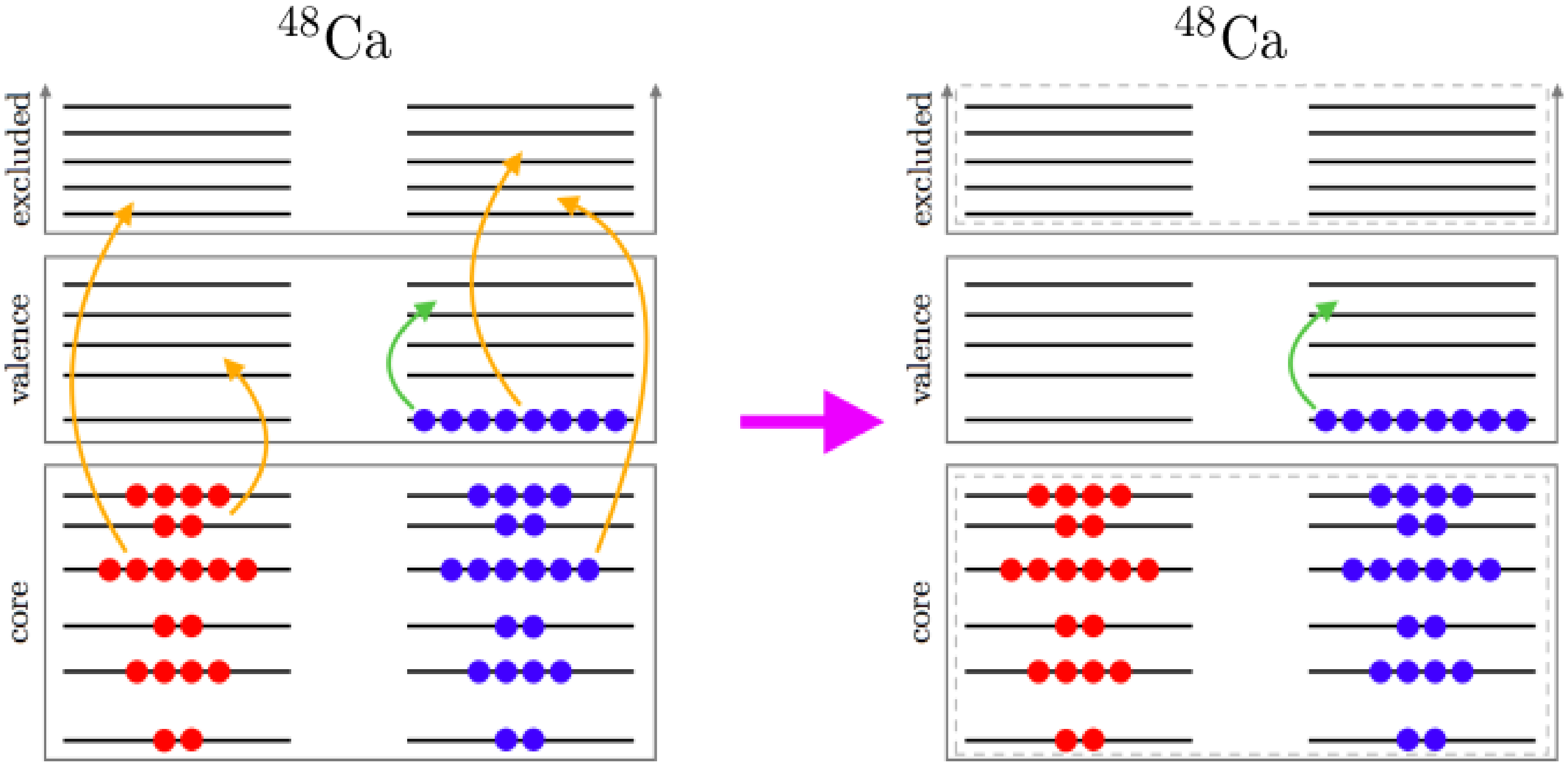
N. Shimizu et al., Phys. Rev. Lett. **120**, 142502 (2018).

TRIUMF VS-IMSRG and First Principles/*Ab Initio* Techniques

Ab initio techniques solve the Schrödinger equation

$$\hat{H}\Psi = E\Psi$$

but the full-space Hamiltonian is difficult to solve...



Courtesy of C. G. Payne's thesis

Steps of VS-IMSRG:

1. Decouple core energy and valence-space Hamiltonian from full-space Hamiltonian
2. Solve the simpler valence space Hamiltonian exactly

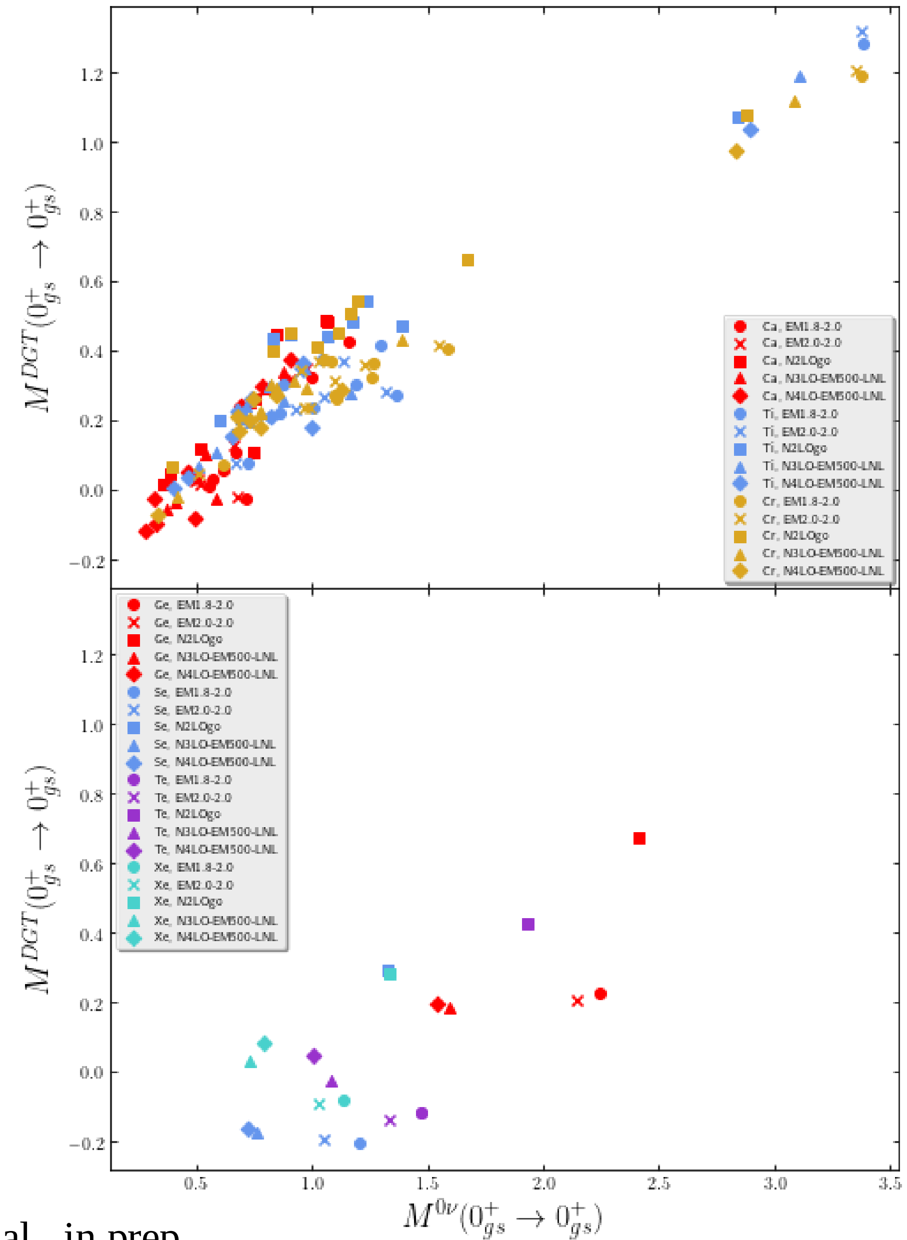
Correlation Plot

Correlation between M^{DGT} and $M^{0\nu}$ Expectation Values

Isotopes considered in the plot (only even mass numbers):

- Ca: 44 < A < 58,
- Ti: 44 < A < 60,
- Cr: 46 < A < 62,
- ^{76}Ge , ^{82}Se , ^{130}Te, ^{136}Xe

Used 5 different NN+3N chiral Hamiltonians



I. Ginnett, A. Belley, T. Miyagi et al., in prep.

TRIUMF

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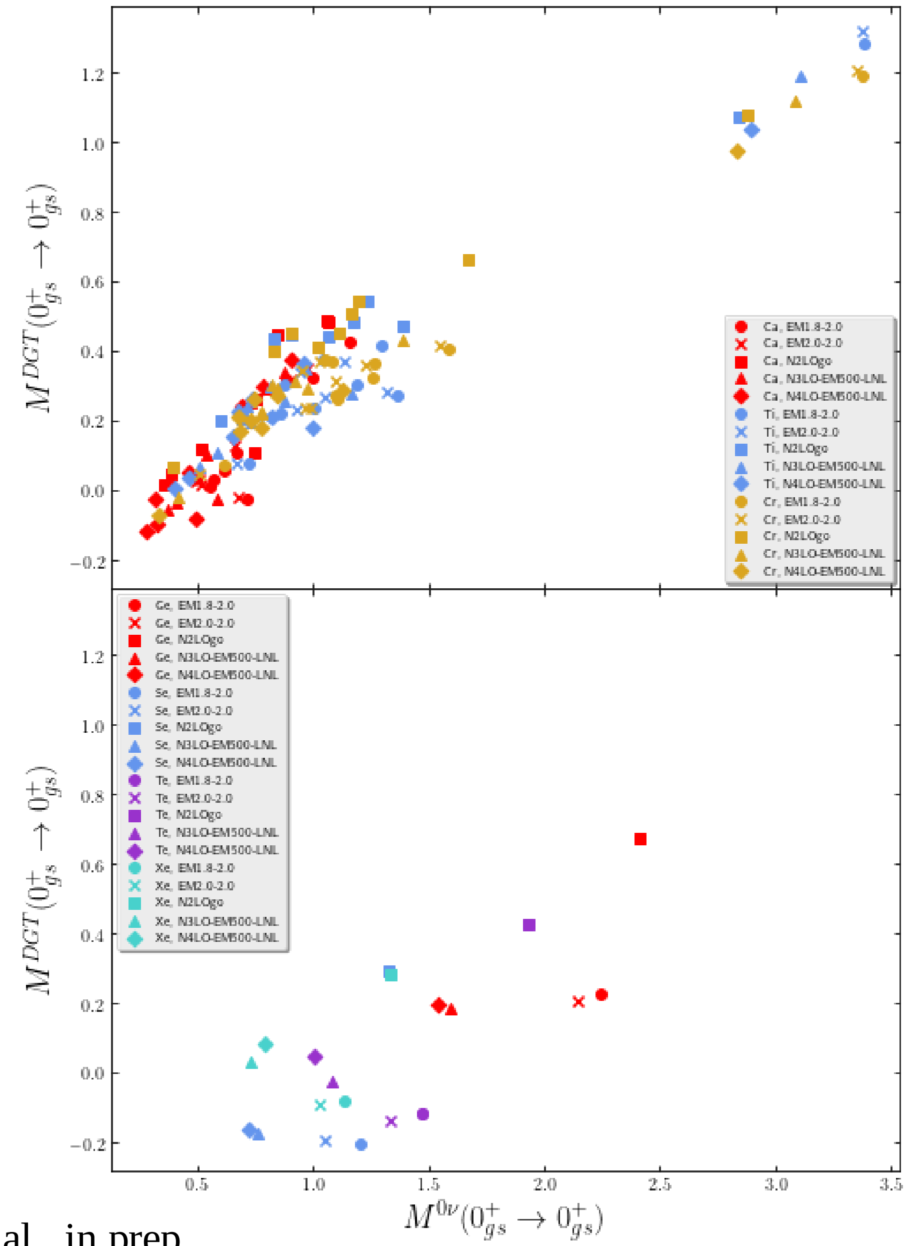

We still see a strong linear correlation between DGT NMEs and 0νββ NMEs!

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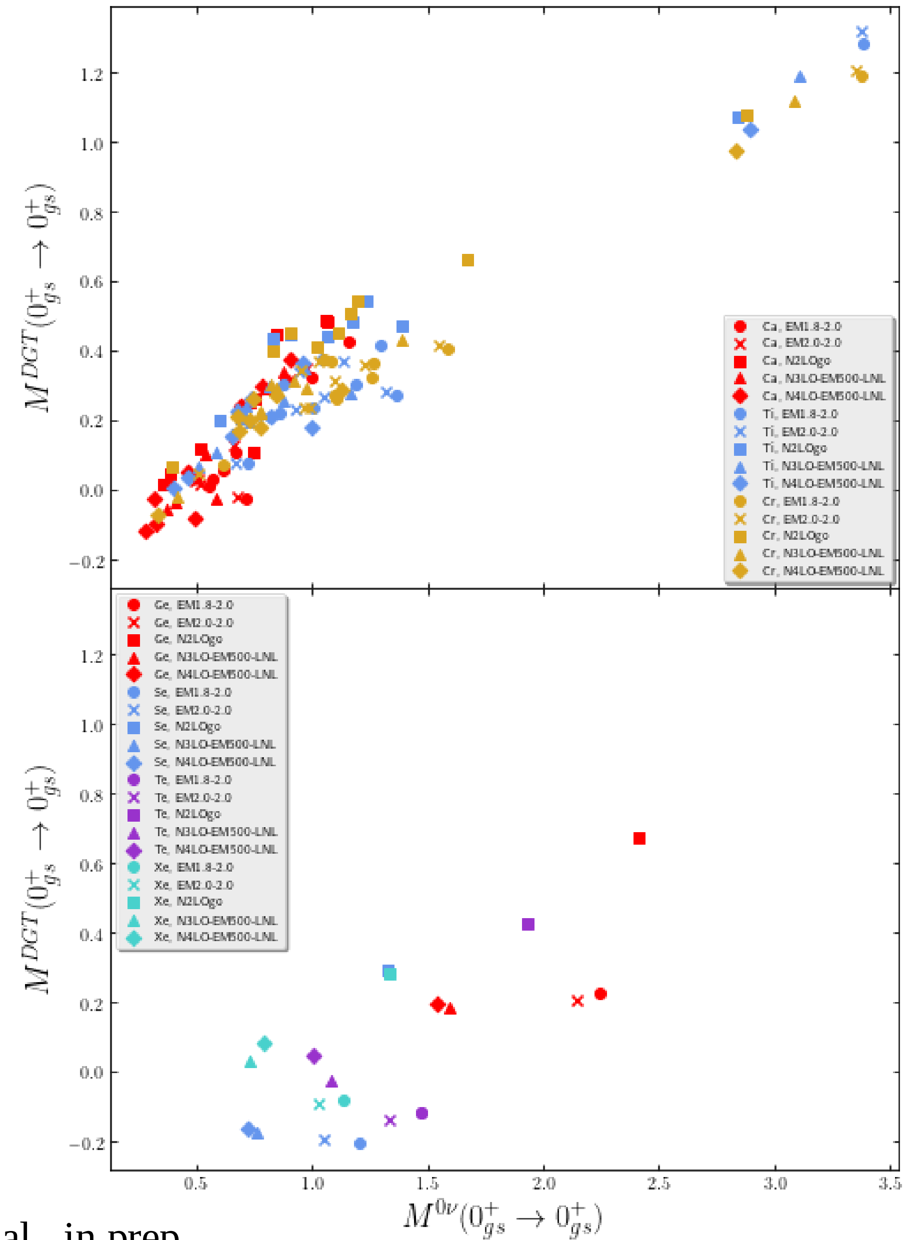


We still see a strong linear correlation between DGT NMEs and 0νββ NMEs!

This means that a process allowed by the Standard Model can constrain a Beyond-Standard-Model process.

I. Ginnett, A. Belley, T. Miyagi et al., in prep.

Summary

- Experimental observation of $0\nu\beta\beta$ can have a big impact on our understanding of physics.
- Precise NME calculations are critical to constraining experimental searches.
- Previous results showed that there was a linear correlation between DGT transition NMEs and $0\nu\beta\beta$ decay NMEs.
- We showed that this linear correlation still holds when using the first principles computational technique known as VS-IMSRG.

TRIUMF

Acknowledgements

I would like to thank the following people for their support and guidance:

- J. Holt
- A. Belley
- T. Miyagi
- S. R. Stroberg
- E. Love

I would also like to thank Mitacs and Fulbright Canada for funding this experience and TRIUMF and the University of British Columbia for making this research experience possible.

UBC

Mitacs Globalink

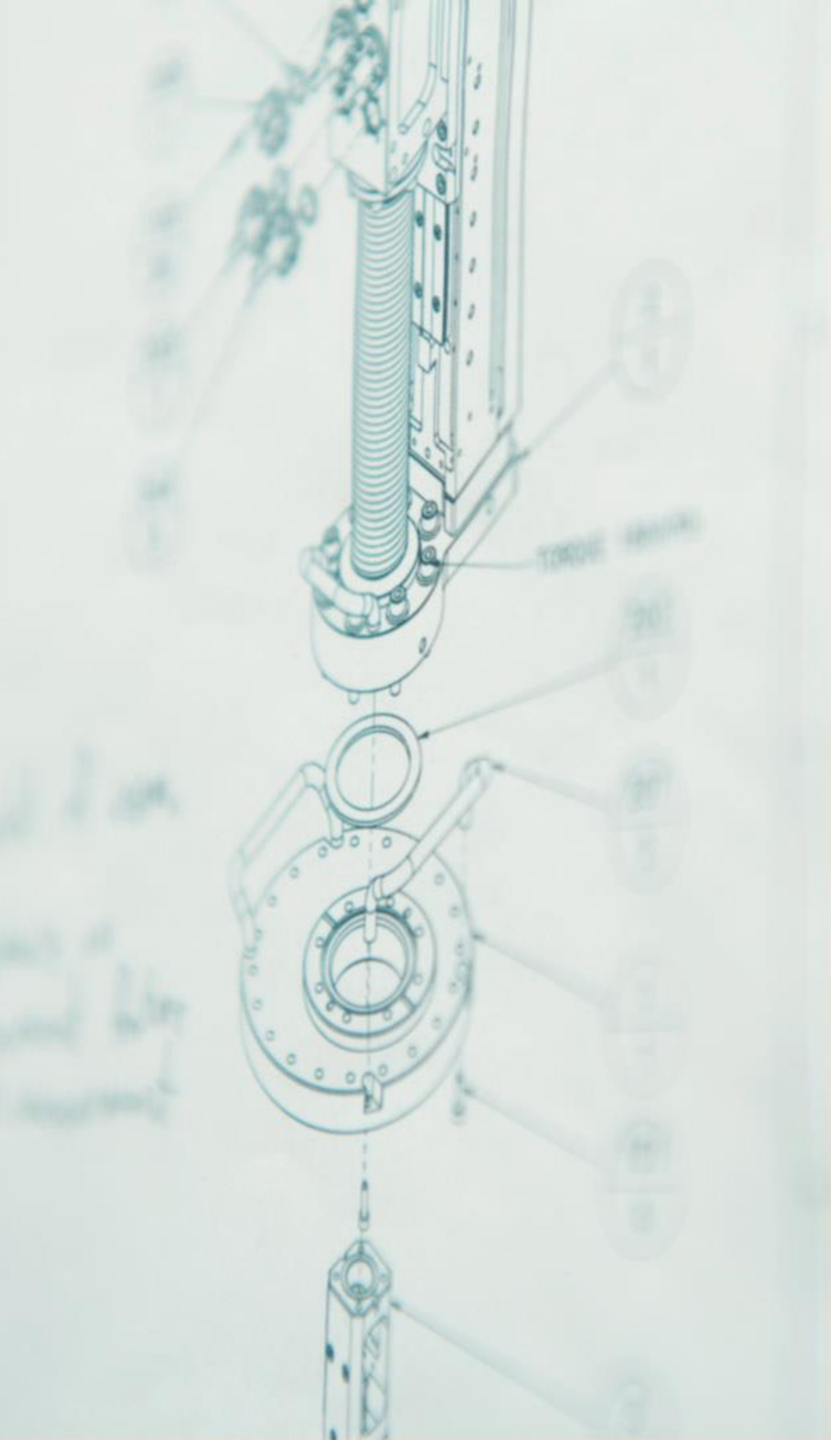
FULBRIGHT Canada

TRIUMF

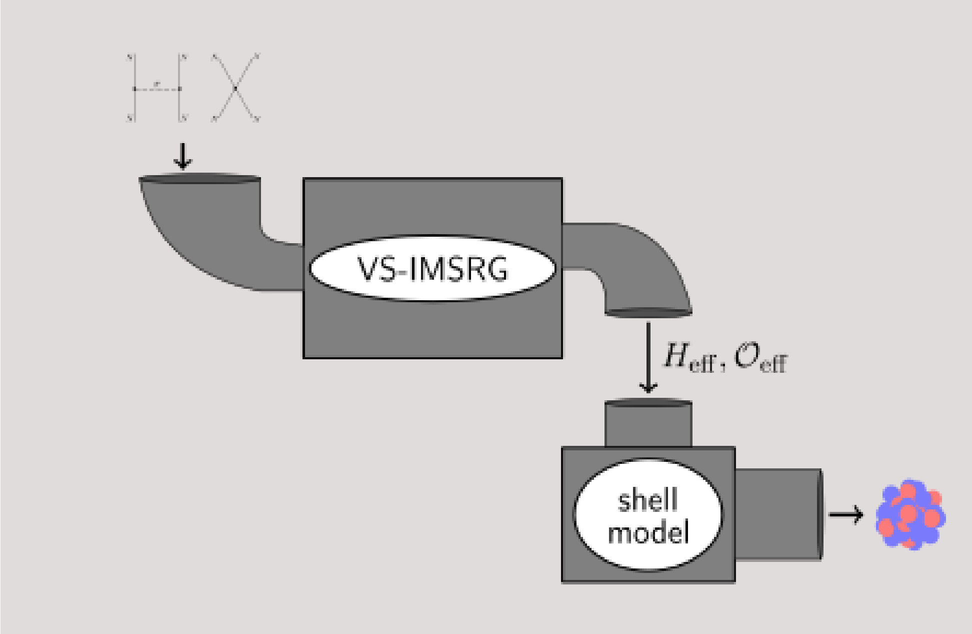
Thank you! Are there any questions?

Discovery, accelerated

Additional Slides



VS-IMSRG and First Principles/*Ab Initio* Techniques



Courtesy of S. R. Stroberg

Important parameters:

- e_{max} : harmonic oscillator basis size ($2n + l \leq e_{max}$)
- $E3_{max}$: 3-body force truncation (ideally $E3_{max} = 3 \cdot e_{max}$)
- $\hbar\omega$: harmonic oscillator frequency

Note: all operators are currently truncated at the 2-body level

Steps of VS-IMSRG:

1. Decouple core energy and valence-space Hamiltonian from full-space Hamiltonian
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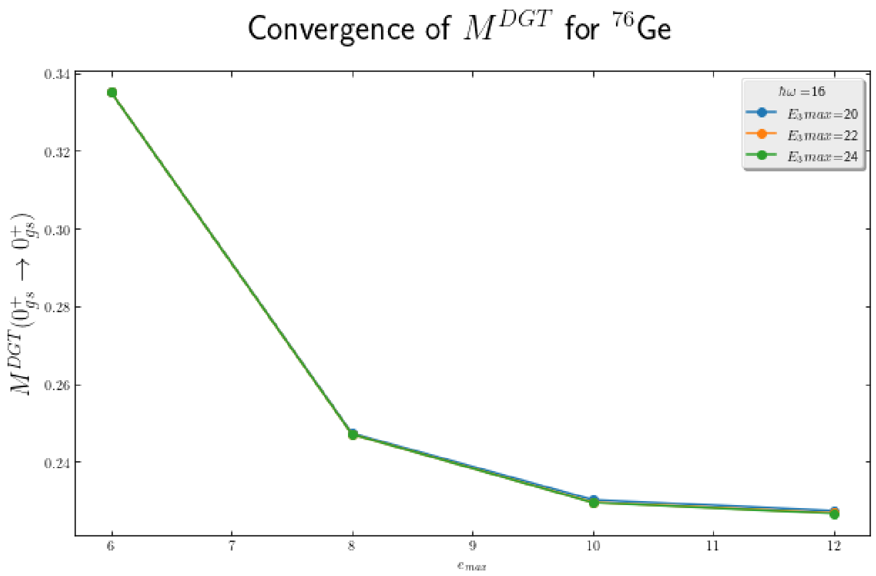
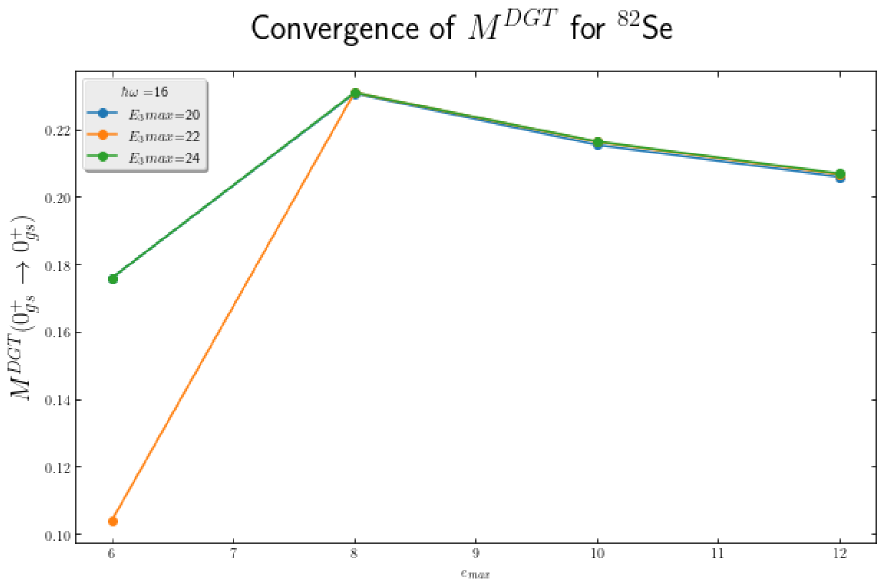
Convergence Checks





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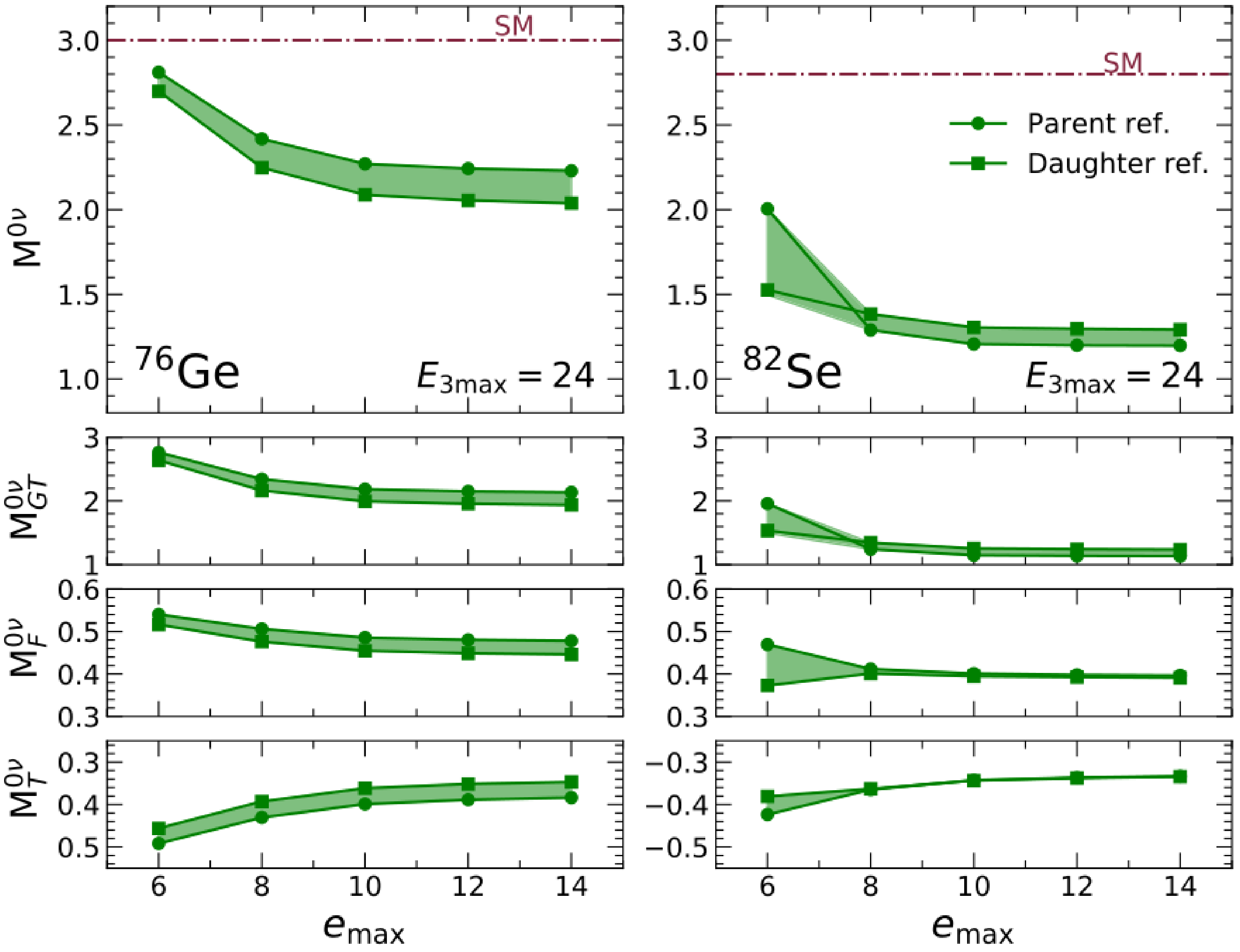

A. Belley et al., Phys. Rev. Lett. **126**, 042502 (2021).

Experimentally Observing DGT

- Experimentally, DGT is yet to be observed.
- Lots of experimental interest!
- Current experimental searches use heavy ion double charge exchange interactions.
- M. Takaki et al. used $^{12}C(^{18}O,^{18}Ne)^{12}Be$ to probe DGT transitions [1].
- K. Takahisa et al. used and $^{13}C(^{11}B,^{11}Li)^{13}O$ and $^{56}Fe(^{11}B,^{11}Li)^{56}Ni$ [2].
- More experiments need to be done.

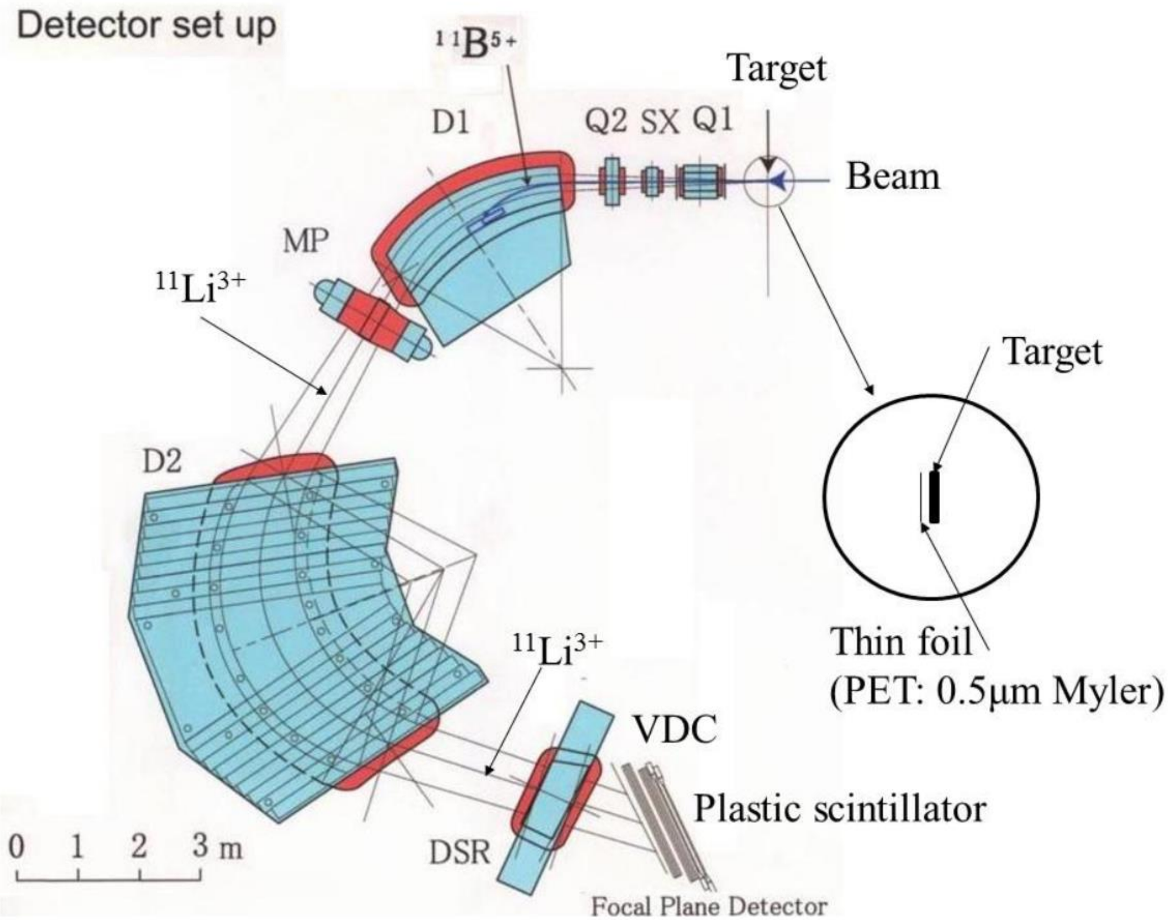

Diagram of the Grand Raiden spectrometer, Osaka University [2].

[1] M. Takaki et al., JPS Conf. Proc. **6**, 020038 (2015).
[2] K. Takahisa et al., arXiv:1703.08264, (2017).