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Neutrino(less) Double Beta Decay

An experimentalist's perspective

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Why 0νββ are important for NuSTEC?

- Low energy ν-nucleus scattering expected to be the main limitation in direct dark matter search experiments.
- ν-nucleus scattering modelling is one of the main limitations in oscillation measurements, and to further look for CP-violation within the lepton sector via oscillations.
- The direct observation of 0νββ can uniquely prove **lepton number violation** (a matter creation mechanism!), and the **Majorana nature of neutrinos**, also our best strategy for **determining the absolute neutrino-mass scale** at the level of few tens of meV. Sensitivities are driven by the **Nuclear Matrix Element (NME). NME formulation is driven by the BSM mechanism! (nuclear&BSM are convoluted!)**

Why 0vββ?

A Majorana particle needs to have mass, to have spin ½, and its charge must be zero. The only fermions that can satisfy the Majorana condition are the neutrinos!

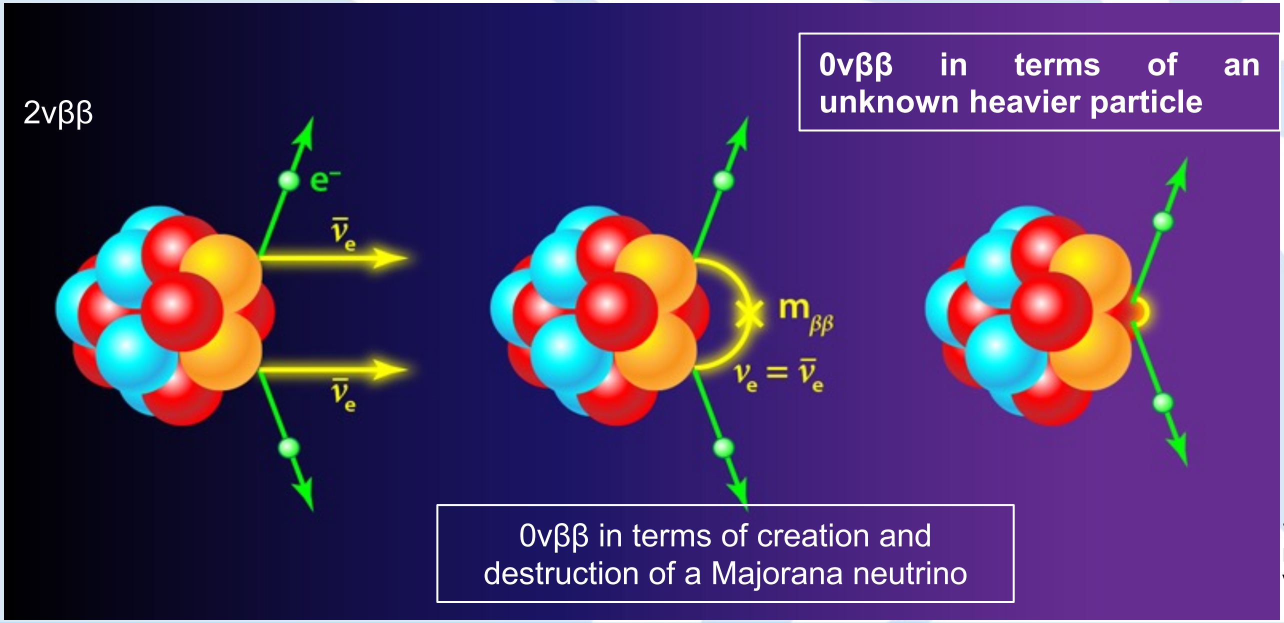
Majorana neutrinos are a low energy prediction of leptogenesis, compelling mechanism for the matter/antimatter asymmetry. If neutrinos are both Majorana and CP-violating, they could be the answer to this asymmetry.

The search of Majorana neutrinos is strongly motivated!

Why 0νββ?

The detection of the L-violation in 0νββ (ΔL=2) will prove a Majorana fermion.

- The experimentally allowed half-life of the process (from existing constraints) is $T^{1/2}$->10^{26} years
- 0νββ rate is suppressed by a factor m^2/E^2. If neutrino were massless, or not Majorana, the 0νββ rate would be zero.
- If the mechanism is by creation and destruction of Majorana particles, the measurement will also tell us the weighted average of the masses of the three neutrino mass states. If the mechanism involves the existence of a new heavy particle, the relation between the rate and the masses will be more complex.
- One of the most challenging backgrounds is the 2νββ SM allowed process.



Source: The hunt for no neutrinos. J. Engel & P. Vogel. Physics 11, 30, 2018

Nuclear Matrix Elements

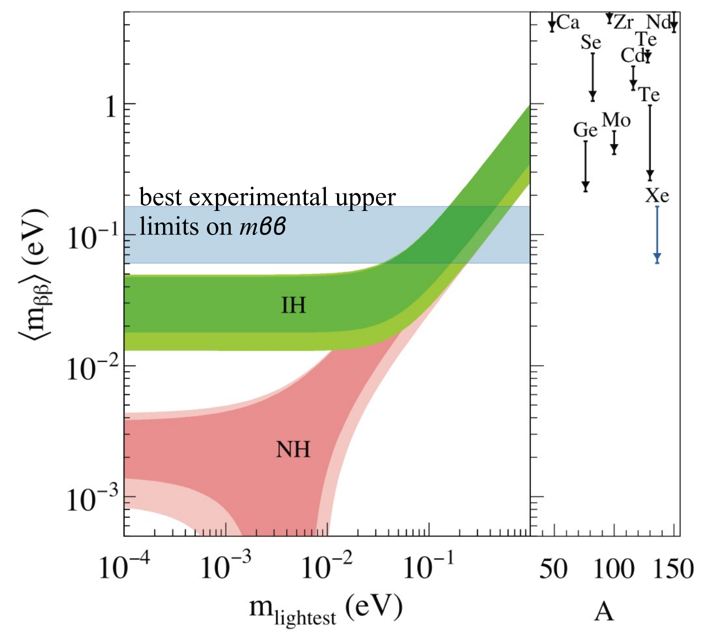
If $0\nu\beta\beta$ is observed it will require complementary experiments to confirm (preferably with different isotopes), and we will want to understand the mechanism of the decay (light or heavy particles?).

Because the decay takes place inside the nuclei, the amount of material required to cover the inverted-hierarchy region depends not only on the neutrino masses, but also on the NME of a two-nucleon operator between the ground states of the decaying nucleus and its decay product.

$0\nu\beta\beta$ involves not only nuclear physics but also unknown neutrino properties (i.e. neutrino mass scale) the NMEs cannot be measured, they must be calculated!

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2 m^2_{\beta\beta}$$

Decay amplitude: $<m_{\beta\beta}>$
M_{0v}: nuclear matrix element
$G_{0v}(Q,Z)$: Q= E_i-E_f, and G_{0v} comes form the phase-space integral



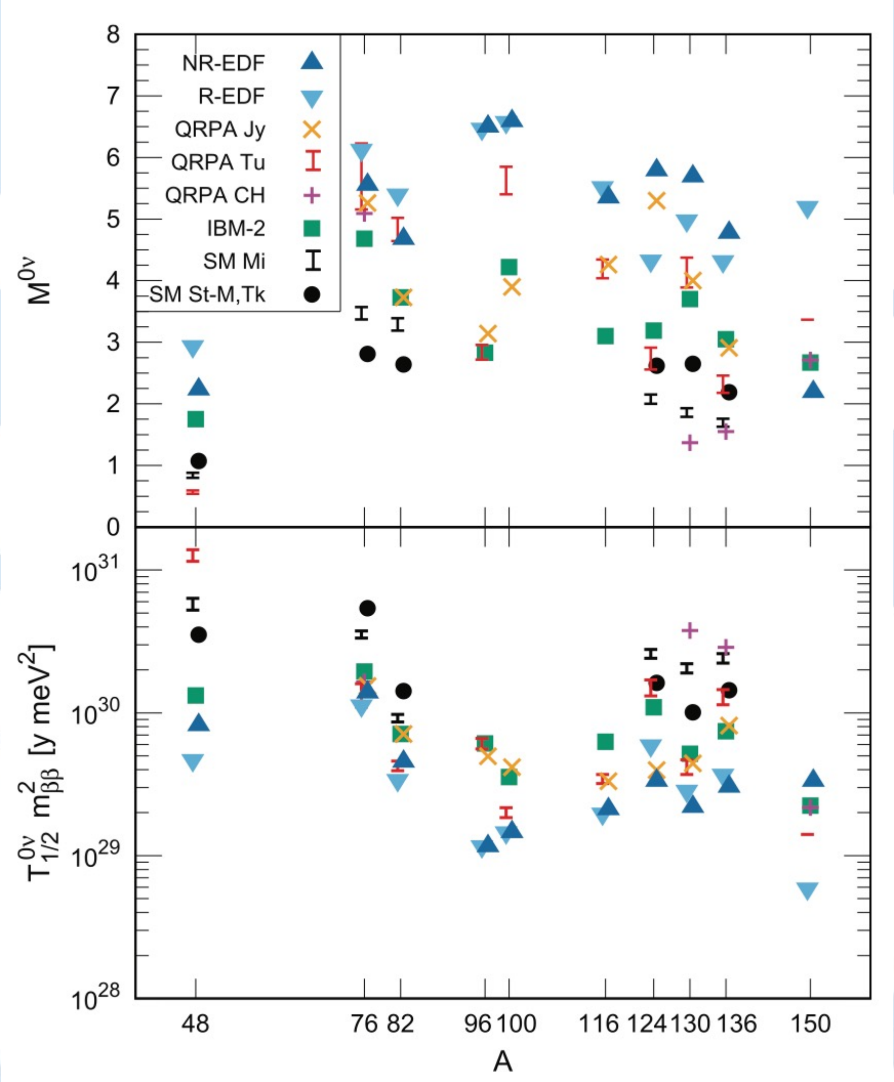
Besides the challenge of producing a background-free experiment (such as NEXT), NME remains as the main systematic.

Nuclear Matrix Elements

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2 m^2_{\beta\beta}$$

Amazing progress from *ab initio* folks delivering (now!) improved results to resolve the puzzle!
Saori Pastore is one of the contributors of the work, and one of the SnowMass 0vββ theory leaders.

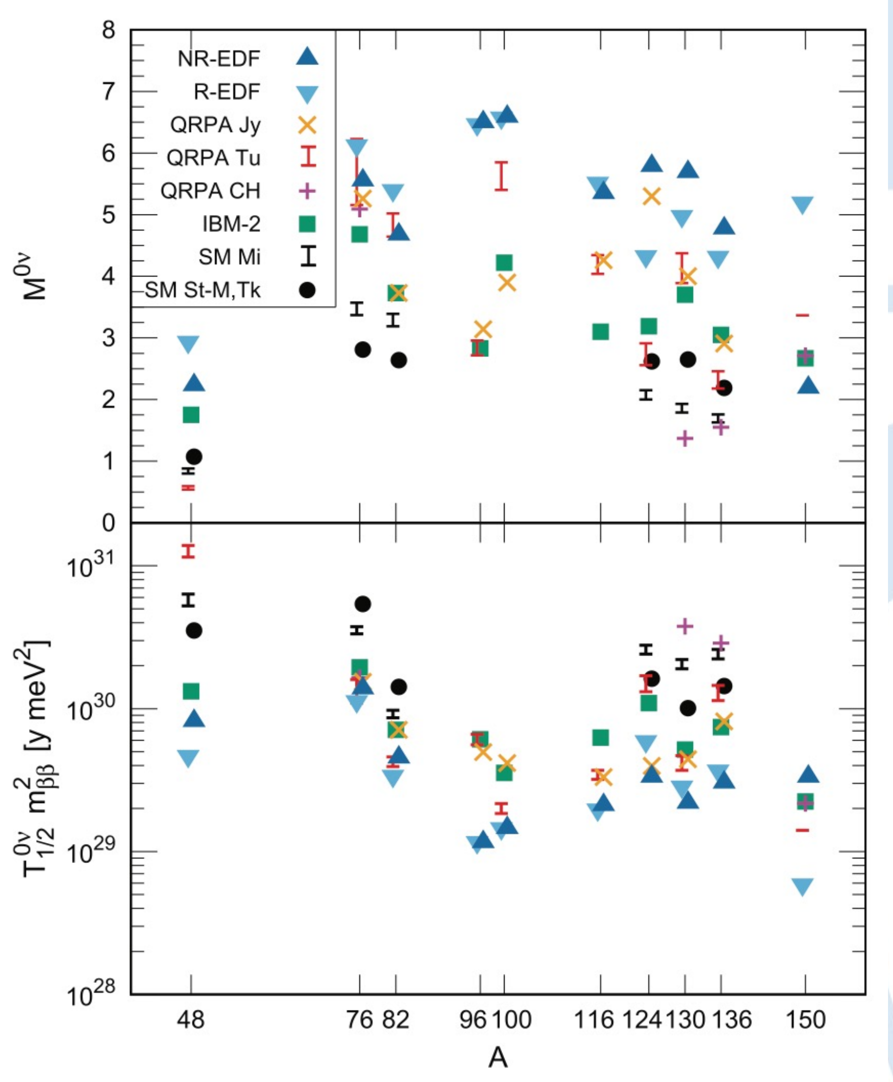
(for detailed discussion on NME, and recent progress, she is the expert)



Nuclear Matrix Elements

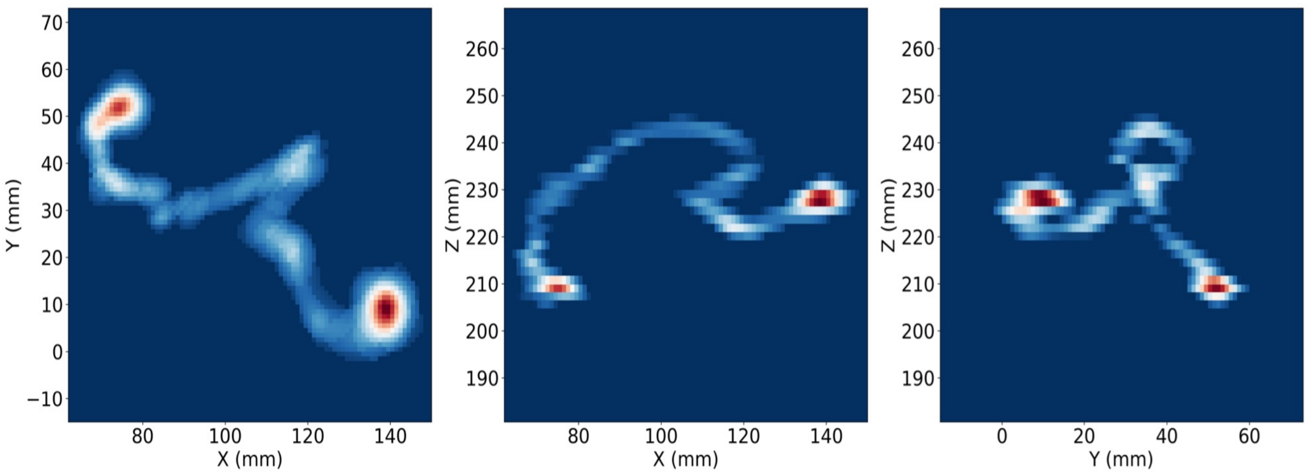
$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2 m^2_{\beta\beta}$$

Main aspect of the new calculations includes a new leading-order short-range operator, with coupling g_v^{NN} (missing in all calculations on Figure) . See Physical Review Letters 120, 202001 (2018)



And what about 2vββ?

While discussions are still need to understand the 0vββ rates and how to determine the decaying mechanism, current experiments provide (and will continue to provide) 2vββ rates. Furthermore, experiments as NEXT provide full topology and kinematic of the decayed electrons in the 2vββ process.



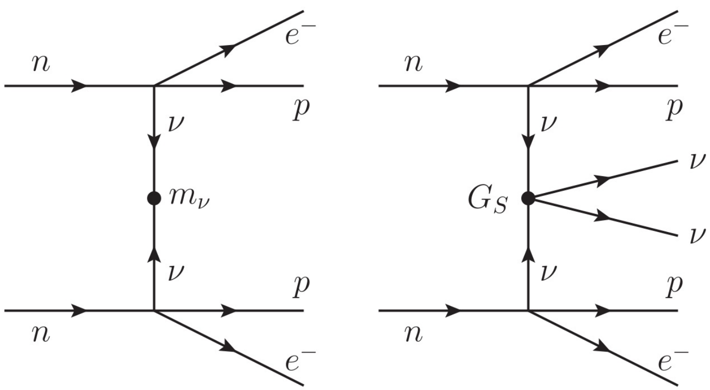
Experimental data from calibration runs (^{208}Tl) in the 1.6 MeV double escape peak after topological classification using RL-deconvolution at NEXT. arXiv:2120.11931v3

The first NEXT paper measuring 2vββ ^{136}Xe event rate is coming out in few days!

$$[T^{2\nu}_{1/2}]^{-1} = G_{2\nu}(Q,Z)\left|M^{2\nu}_{\mathrm{GT}} - \frac{g_V^2}{g_A^2} M^{2\nu}_F\right|^2$$

Does not depend on neutrino masses or charge-conjugation properties. But its measurement can constraint or indicate BSM physics.
For example, measuring this rate and its kinetical properties may lead to vSI (v self-interactions).

And what about 2νββ?



Introducing a νSI (a four-neutrino contact interaction), to inhibit neutrino freestreaming in the early Universe could resolve the Hubble tension (see PRD 102, 051701(R)).

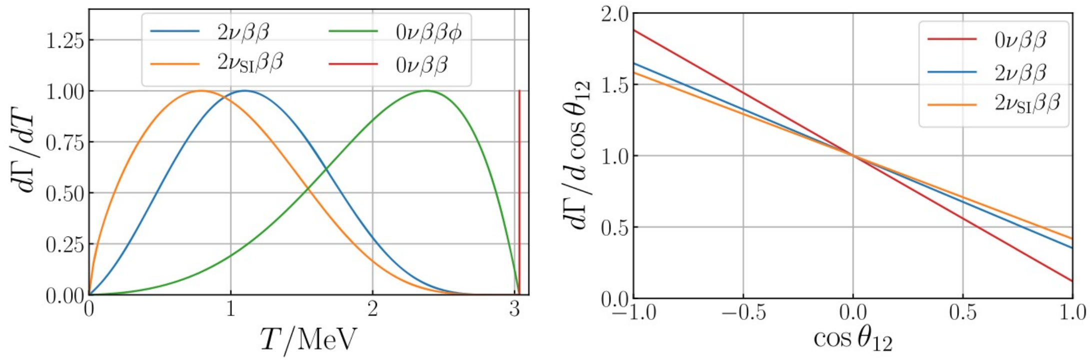


FIG. 4. Energy (left panel) and angular (right panel) distributions of $2\nu_{SI}\beta\beta$, in comparison with other types of $\beta\beta$ decay. All spectra are normalized to 1 at the peaks (left) or at $\cos\theta_{12} = 0$ (right), so the figure is in arbitrary units.

How NuSTEC could support 0νββ searches?

Advance in technology for 0nuBB searches has open the possibility of study more than rates, we have access now to the event kinematics and even nuclear recoil information. **But we don't have event generators!**

There is now some simulation available for rates, but not at the level of event generator we propagate on our detector simulation. A path forward to catch up with experimental development is to create an event generator that including some of the models for both, 0νββ and 2νββ with information one:

- **Electron kinematics**
- **Nuclear recoils**
- Support for different models of 0νββ (creation/destruction mechanism, heavy particles) and 2νββ (there are different scenarios BSM we would like to investigate, and much more we wantto heard from the theory community).

How NuSTEC could support 0νββ searches?

Traditionally, nuclear physics interplays with neutrino physics experiments because of the strategies to measure oscillations. NuSTEC was formed to support the neutrino experimental community in the search of BSM physics, as a nuclear-neutrino physics bridge.

The sensitivity to observe the forbidden 0νββ nuclear processes, which observation will change the way we understand the Universe, depends on the NME. The measured rate will provide insights of the decaying mechanism.

Also, the precise measurement of 2νββ (whose NME are different from 0νββ, as $\Delta L=0$) can provide insights of additional BSM processes.

0νββ/2νββ are nuclear process which interplay with neutrino properties comes different, stronger, fully convoluted.

Understand our sensitivities, and to successfully interpret our results requires theory-experimental communication. To further design improved analyses requires us to understand theory inputs, an **event generator will be ideal!**

NuSTEC has been successful providing space (conference, workshops,…) for communication, and could be a good place for 0νββ discussion and tool sharing.

A discovery may be around the corner…

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