On the importance of muon capture for neutrinoless double-beta decay studies

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ICCUB

Creation of matter in nuclei: $0\nu\beta\beta$ decay

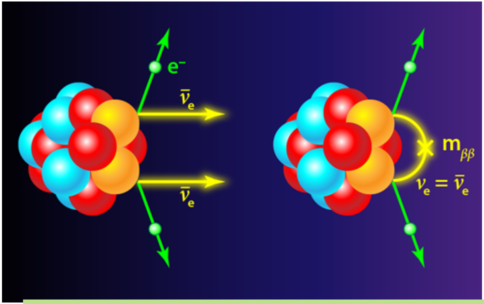
Lepton number is conserved in all processes observed:

single β decay,
$\beta\beta$ decay with neutrino emission...

Uncharged massive particles like Majorana neutrinos (ν) allow lepton number violation:

neutrinoless $\beta\beta$ decay
two matter particles (electrons) created

Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. in press, arXiv:2202.01787



Nuclear matrix elements for new-physics searches

Neutrinos, dark matter studied in experiments using nuclei

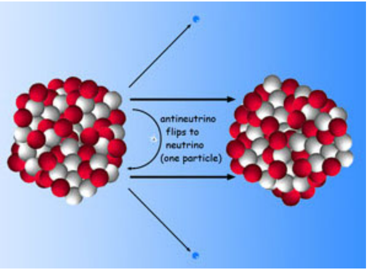
Nuclear structure physics
encoded in nuclear matrix elements
key to plan, fully exploit experiments

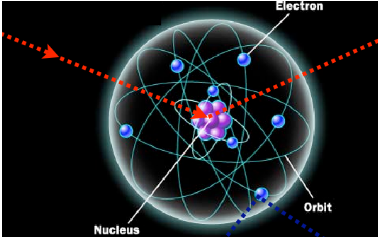
$$0\nu\beta\beta\text{:}\ \left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4 \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$$

$$\text{Dark matter:}\ \frac{d\sigma_{\chi\mathcal{N}}}{d\boldsymbol{q}^2} \propto \left|\sum_i c_i\,\zeta_i\,\mathcal{F}_i\right|^2$$

$$\text{CE}\nu\text{NS:}\ \frac{d\sigma_{\nu\mathcal{N}}}{d\boldsymbol{q}^2} \propto \left|\sum_i c_i\,\zeta_i\,\mathcal{F}_i\right|^2$$

$M^{0\nu\beta\beta}$: Nuclear matrix element
$\mathcal{F}_i$: Nuclear structure factor

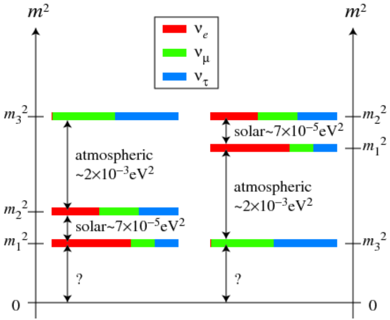


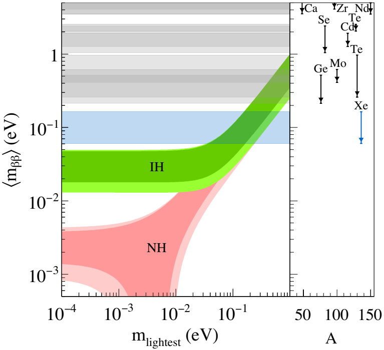


Next generation experiments: inverted hierarchy

Decay rate sensitive to neutrino masses, hierarchy
$m_{\beta\beta} = |\sum U_{ek}^2 m_k|$

$$T_{1/2}^{0\nu\beta\beta}\left(0^+ \to 0^+\right)^{-1} = G_{0\nu}\, g_A^4 \left|M^{0\nu\beta\beta}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$





Matrix elements assess if next generation experiments fully explore "inverted hierarchy"

KamLAND-Zen, PRL117 082503(2016)

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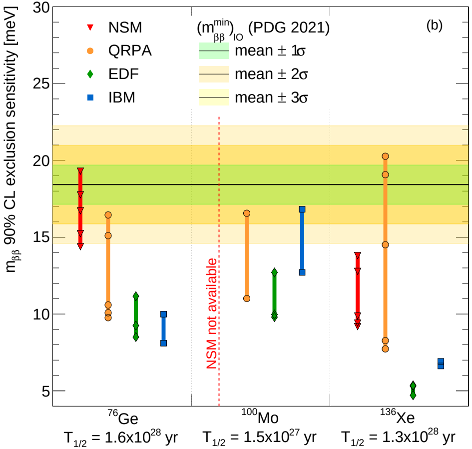
Uncertainty in physics reach of $0\nu\beta\beta$ experiments



Agostini, Benato, Detwiler, JM, Vissani
Phys. Rev. C 104 L042501 (2021)

Nuclear matrix element theoretical uncertainty critical to anticipate $m_{\beta\beta}$ sensitivity of future experiments

Current uncertainty in $m_{\beta\beta}$ prevents to foresee if next-generation experiments will fully cover parameter space of “inverted” neutrino mass hierarchy

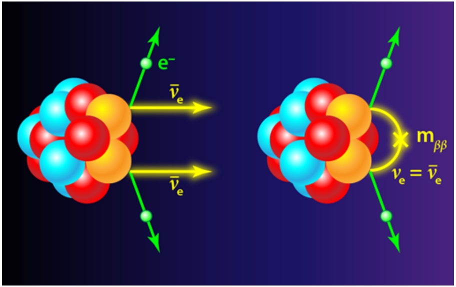
Uncertainty needs to be reduced!

Nuclear matrix elements

Nuclear matrix elements needed in low-energy new-physics searches

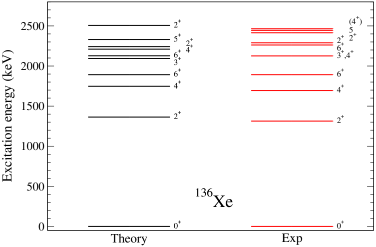
$$\langle \text{Final} \,|\, \mathcal{L}_{\text{leptons}-\text{nucleons}} \,|\, \text{Initial} \rangle = \langle \text{Final} \,|\, \int dx\, j^{\mu}(x) J_{\mu}(x) \,|\, \text{Initial} \rangle$$

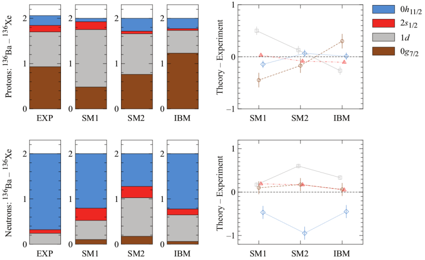
- Nuclear structure calculation of the initial and final states:
  Shell model, QRPA, IBM,
  Energy-density functional
  Ab initio many-body theory
  QMC, Coupled-cluster, IMSRG...
- Lepton-nucleus interaction:
  Hadronic current in nucleus:
  phenomenological,
  effective theory of QCD



Tests of nuclear structure

Spectroscopy well described: masses, spectra, transitions, knockout...



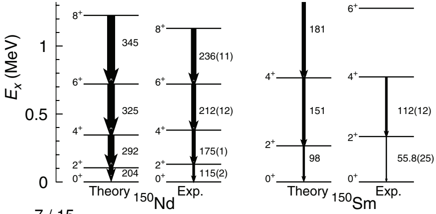


Schiffer et al. PRL100 112501(2009)

Kay et al. PRC79 021301(2009)

...

Szwec et al., PRC94 054314 (2016)



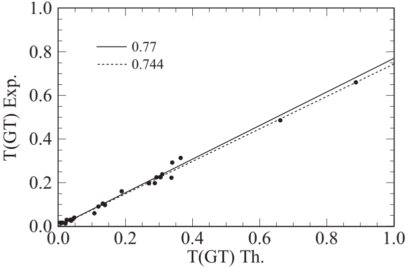
Rodríguez et al. PRL105 252503 (2010)

...

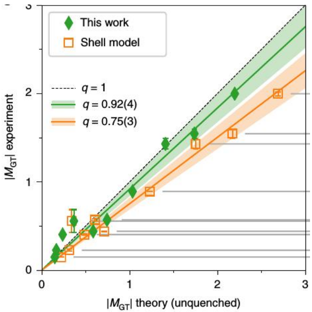
Vietze et al. PRD91 043520 (2015)

β–decay Gamow-Teller transitions: “quenching”

β decays (e^- capture): phenomenology vs ab initio



Martinez-Pinedo et al. PRC53 2602(1996)



Gysbers et al. Nature Phys. 15 428 (2019)

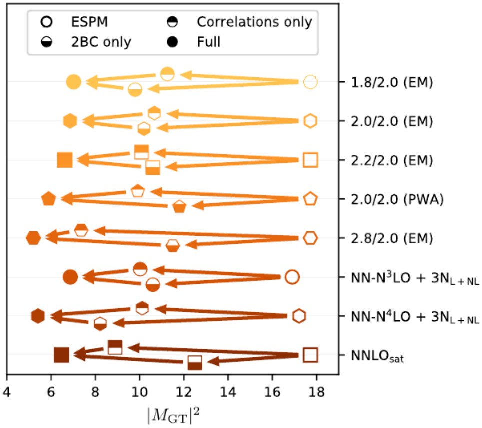
$$\langle F | \sum_i [g_A\, \boldsymbol{\sigma}_i \tau_i^-]^{\text{eff}} | I \rangle \,, \quad [\boldsymbol{\sigma}_i \tau]^{\text{eff}} \approx 0.7 \boldsymbol{\sigma}_i \tau$$

Standard shell model needs $\boldsymbol{\sigma}_i \tau$ “quenching”

Ab initio calculations including meson-exchange currents and additional nuclear correlations do not need any “quenching”

Origin of β decay "quenching"

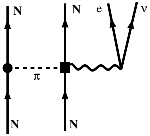
Which are main effects missing in conventional β-decay calculations?
Test case: GT decay of ^{100}Sn



Relatively similar and complementary impact of

- nuclear correlations
- meson-exchange currents

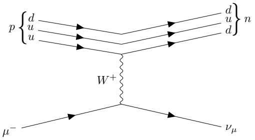
Gysbers et al.
Nature Phys. 15 428 (2019)

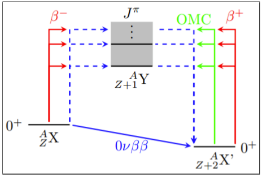


Muon capture

TRIUMF

Ordinary Muon Capture (OMC) vs. $0\nu\beta\beta$





$$\mu^- + {}^{A}_{Z}\mathrm{X}(J_i^{\pi_i}) \rightarrow \nu_\mu + {}_{Z-1}^{A}\mathrm{Y}(J_f^{\pi_f})$$

- Weak interaction process with momentum transfer $q \approx 100\ \mathrm{MeV}/c^2$
- Large m_μ allows **transitions to all J^π states** up to high energies

Discovery, accelerated

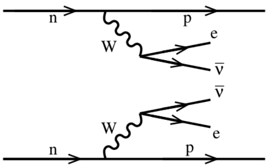
credit: L. Jokiniemi

Two-neutrino $\beta\beta$ decay, 2νECEC

$2\nu\beta\beta$ decay same initial, final states , similar operator ($\sigma\tau$) as $0\nu\beta\beta$
Comparison of predicted $2\nu\beta\beta$ decay vs data

Shell model reproduce $2\nu\beta\beta$ data including “quenching”

Prediction previous to ^{48}Ca measurement!
Caurier, Poves, Zuker
PLB 252 13(1990)



$$M^{2\nu\beta\beta} = \sum_k \frac{\langle 0_f^+ | \sum_n \sigma_n \tau_n^- | 1_k^+ \rangle \langle 1_k^+ | \sum_m \sigma_m \tau_m^- | 0_i^+ \rangle}{E_k - (M_i + M_f)/2}$$

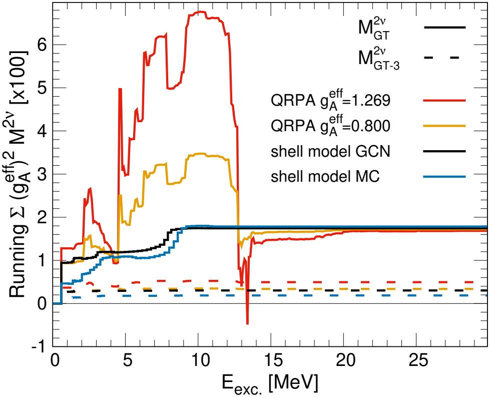
Table 2
The ISM predictions for the matrix element of several 2ν double beta decay (in MeV^{-1}). See text for the definitions of the valence spaces and interactions.

	$M^{2\nu}$(exp)	q	$M^{2\nu}$(th)	INT
^{48}Ca → ^{48}Ti	0.047 ± 0.003	0.74	0.047	kb3
^{48}Ca → ^{48}Ti	0.047 ± 0.003	0.74	0.048	kb3g
^{48}Ca → ^{48}Ti	0.047 ± 0.003	0.74	0.065	gxpf1
^{76}Ge → ^{76}Se	0.140 ± 0.005	0.60	0.116	gcn28:50
^{76}Ge → ^{76}Se	0.140 ± 0.005	0.60	0.120	jun45
^{82}Se → ^{82}Kr	0.098 ± 0.004	0.60	0.126	gcn28:50
^{82}Se → ^{82}Kr	0.098 ± 0.004	0.60	0.124	jun45
^{128}Te → ^{128}Xe	0.049 ± 0.006	0.57	0.059	gcn50:82
^{130}Te → ^{130}Xe	0.034 ± 0.003	0.57	0.043	gcn50:82
^{136}Xe → ^{136}Ba	0.019 ± 0.002	0.45	0.025	gcn50:82

Caurier, Nowacki, Poves, PLB 711 62 (2012)

Running of $2\nu\beta\beta$ matrix elements

Measurements of $\beta\beta$ decay spectra can test calculations with different matrix element as function of energy of intermediate state



Qualitative very different shell model vs QRPA

QRPA also quite different between different g_A^{eff} values (or diff. isoscalar pairing g_{pp})

Smaller QRPA g_A^{eff} preferred in some β-decay studies

Faessler et al.

JPG 35 075104 (2008)

KamLAND-Zen, JM, Dvornicky, Šimkovic, PRL122 192501 (2019)

^{136}Xe $\longrightarrow$ ^{136}Ba 0_2^+ running sums

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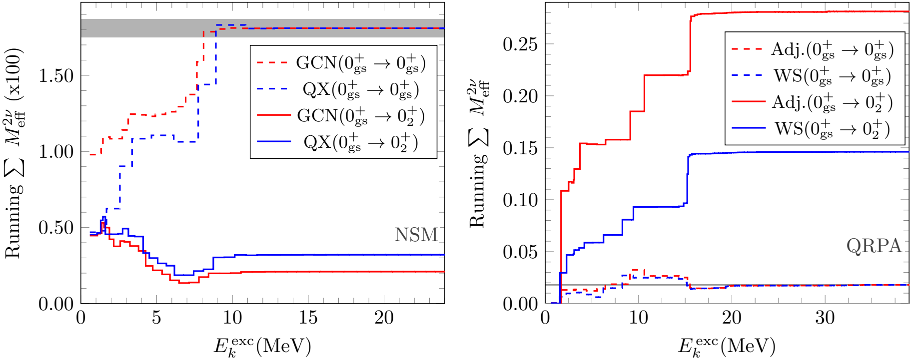
Subtle cancellation NME running sum, depends on many-body method



Jokiniemi, Romeo, Brase, Kotila et al. PLB 838 137689 (2023)

Shell-model running sum shows cancellations in decay to ground state

QRPA running sum shows cancellations in decay to excited state

Test of nuclear structure: GT decays

Shell Model predicts $2\nu\beta\beta$ decay

GT quenching is needed $\Downarrow$

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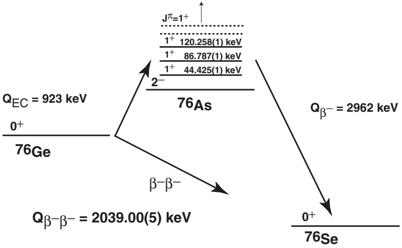
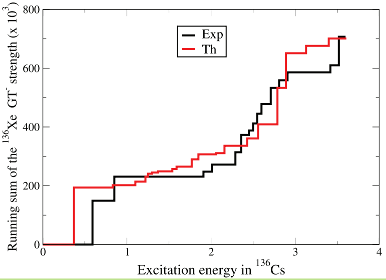
Caurier, Nowacki, Poves PLB711 62(2012)



Gamow-Teller Strengths well reproduced Exp: Puppe et al. PRC84 051305(2011)$\Rightarrow$



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Summary and Outlook

Muon capture provides unique information
of a weak-interaction mediated process
with similar momentum transfer than neutrinoless $\beta\beta$ decay
(only inelastic neutrino scattering can provide similar data
but these experiments are also quiete challenging)

Measurement of partial muon capture rates to individual states
especially in nuclei which can be calculated reliably
(the most controlled calculations correspond to light nuclei)
would provide precious information to test the theoretical calculations