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Double-Beta Decay with Emission of Single Electron

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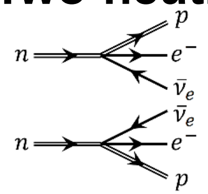
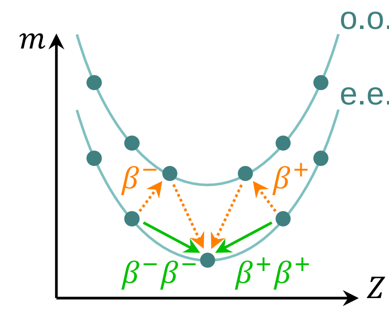
Two-neutrino double-beta decay:



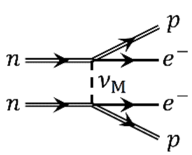
$$2\nu\beta^-\beta^-:\ {}^A_Z\mathrm{X} \longrightarrow {}^{\ \ A}_{Z+2}\mathrm{Y} + \overbrace{e^- + e^- + \bar{\nu}_e + \bar{\nu}_e}^{\Delta L\,=\,0}$$



- Rare 2nd-order process allowed within $\mathcal{L}_{\mathrm{SM}}$ weak interactions
- Observed in 11 out of 35 even-even isotopes: $T_{1/2}^{2\nu\beta\beta} \sim 10^{19} - 10^{21}\ \mathrm{y}$

$$\left(T_{1/2}^{2\nu\beta\beta}\right)^{-1} = g_A^4\, G^{2\nu\beta\beta}(Z,Q)\, \left|m_e\, M^{2\nu\beta\beta}\right|^2$$

Neutrinoless double-beta decay:



$$0\nu\beta^-\beta^-:\ {}^A_Z\mathrm{X} \longrightarrow {}^{\ \ A}_{Z+2}\mathrm{Y} + \overbrace{e^- + e^-}^{\Delta L\,=\,+2}$$

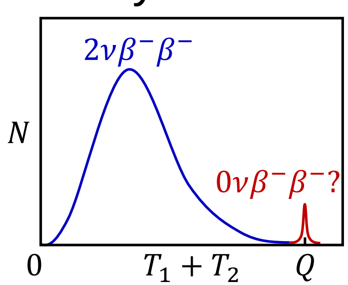
Effective ν_{M} mass:

$$m_{\beta\beta} = \sum_i U_{ei}^2\, m_i$$

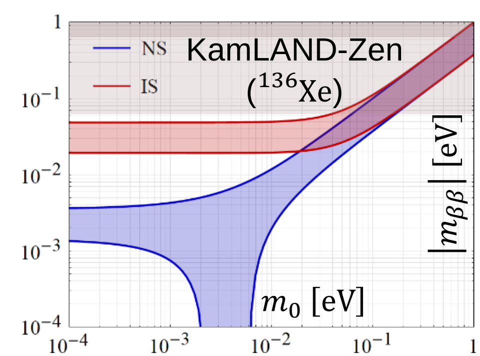
$$|m_{\beta\beta}| < 61 - 165\ \mathrm{meV}$$

- Majorana neutrinos required beyond $\mathcal{L}_{\mathrm{SM}}$: $\nu_i^C(x) = \nu_i(x)$
- Not yet observed: $T_{1/2}^{0\nu\beta\beta} > 10^{25}\ \mathrm{y}\ (90\%\ \mathrm{C.L.})$

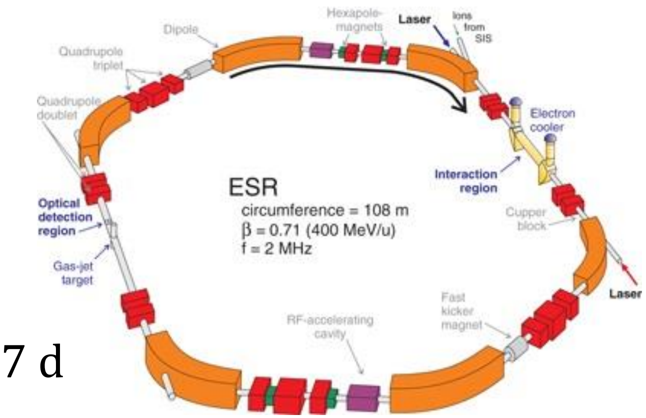
$$\nu_{\alpha L}(x) = \sum_i U_{\alpha i}\, \nu_{iL}(x)$$



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



Introduction: Motivation



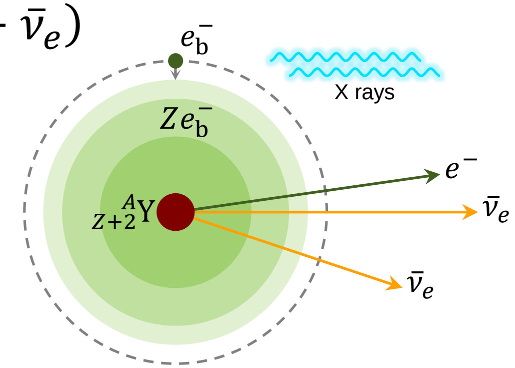
Bound-state beta decay:

$$\mathbf{EP}:\ {}^{A}_{Z}\mathrm{X} \longrightarrow {}_{Z+1}^{\ \ A}\mathrm{Y} + e_{\mathrm{b}}^{-} + \bar{\nu}_e$$

- Electron placement (EP) into atomic K or L shell
- First observed at GSI Darmstadt in ${}^{163}_{66}\mathrm{Dy}^{66+}$: $T_{1/2}^{\mathrm{EP}} = 47$ d
  [Jung *et al.*, *Phys.Rev.Lett.* **69** (1992)]

Neutrinoless (two-neutrino) bound-state double-beta decay:

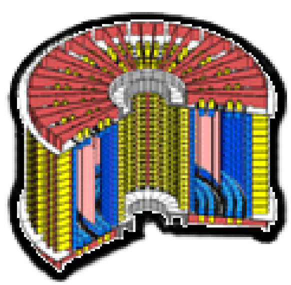
$$\mathbf{0\nu(2\nu)EP\beta^{-}}:\ {}^{A}_{Z}\mathrm{X} \longrightarrow {}_{Z+2}^{\ \ A}\mathrm{Y} + e_{\mathrm{b}}^{-} + e^{-} + (\bar{\nu}_e + \bar{\nu}_e)$$

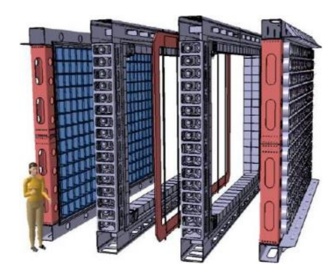


- Electron placement (EP) into available $\mathrm{s}_{1/2}$ or $\mathrm{p}_{1/2}$ subshell
- No effect on calorimetry, but on single-electron spectra!

Tracking & calorimetry experiments at LSM (Modane):

- **NEMO-3** (2003 – 2011):
  - ${}^{100}\mathrm{Mo}$ (7 kg), ${}^{82}\mathrm{Se}$, ${}^{130}\mathrm{Te}$, ${}^{116}\mathrm{Cd}$, ${}^{150}\mathrm{Nd}$, ${}^{96}\mathrm{Zr}$, ${}^{48}\mathrm{Ca}$
  - 700,000+ events with high S/B for ${}^{100}\mathrm{Mo}$ during 3.49 y
- **SuperNEMO** (under construction):
  - ${}^{82}\mathrm{Se}$ (100 kg), ${}^{150}\mathrm{Nd}$ or ${}^{48}\mathrm{Ca}$
  - 1st module "Demonstrator" ready (November 2017)





Calculation: Relativistic Electron Wave Functions

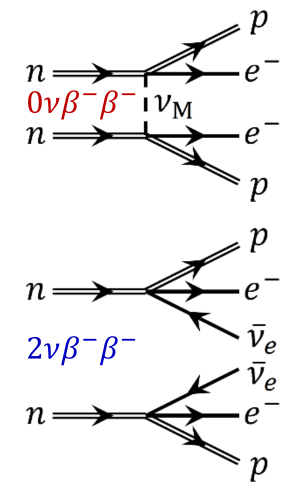
Effective beta-decay Hamiltonian:

$$G_\beta = G_\mathrm{F} \cos\theta_\mathrm{C}$$

$$\mathcal{H}_\beta(x) = \frac{G_\beta}{\sqrt{2}}\, \bar{e}(x)\, \gamma^\mu\, (1-\gamma^5)\, \nu_e(x)\, j_\mu(x) + \mathrm{H.c.}$$

$$j_\mu(x) = \bar{p}(x)\, \gamma_\mu\, (g_V - g_A\, \gamma^5)\, n(x)$$

$$g_V = 1 \quad g_A = 1.27$$



Relativistic electron wave functions in central field:

$$\psi_{\kappa\mu}(\vec{r}) = \begin{pmatrix} f_\kappa(r)\, \Omega_{\kappa\mu}(\hat{r}) \\ i g_\kappa(r)\, \Omega_{-\kappa\mu}(\hat{r}) \end{pmatrix}$$

$$j = |l \pm 1/2|$$

$$\kappa = (l-j)(2j+1) = \pm 1, \pm 2, \ldots$$

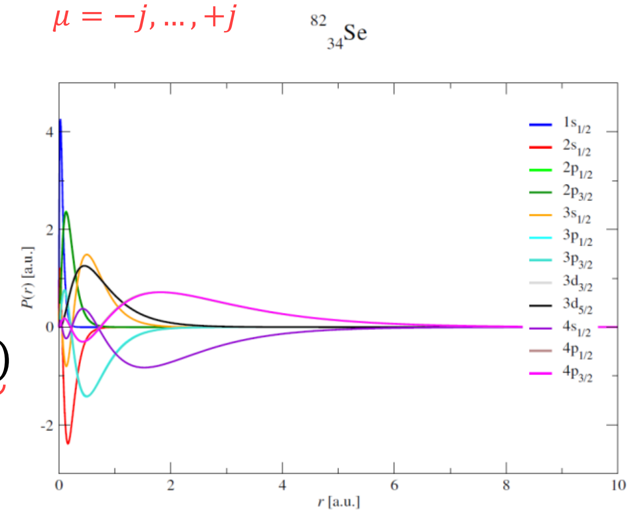
$$\mu = -j, \ldots, +j$$

Bound- and free-electron Fermi functions:

$$B_n(Z,A) = \underbrace{f_{n,-1}^2(R)}_{ns_{1/2}} + \underbrace{g_{n,+1}^2(R)}_{np_{1/2}}$$

$$R = 1.2\ \mathrm{fm}\ A^{1/3}$$

$$F(Z,E) = \underbrace{f_{-1}^2(R,E) + g_{+1}^2(R,E)}_{s_{1/2}\ \text{wave}}$$



Dominant $s_{1/2}$ term from partial-wave expansion:

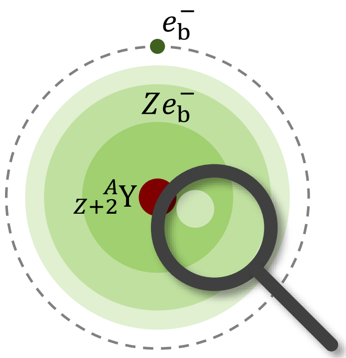
$$F(Z,E) \approx 4 \left[\frac{|\Gamma(\gamma + i\nu)|}{\Gamma(2\gamma+1)} \right]^2 (2pR)^{2\gamma-2}\, e^{\pi\nu}$$

$$\gamma = \sqrt{\kappa^2 - (\alpha Z)^2}$$

$$\nu = \alpha Z E / p$$

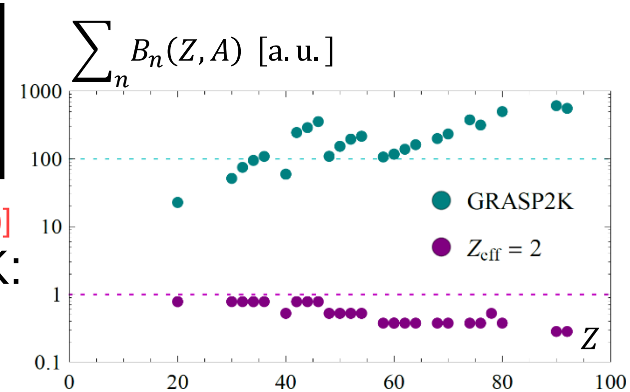
CALCULATION: GRASP2K

Stationary N-particle Dirac eq. with separable central atomic Hamiltonian $[\mathrm{a.u.}]$:



$$\left[\sum_{i=1}^{N} -i\nabla_i \cdot \vec{\alpha} c + \beta c^2 - \frac{Z}{r_i} + V(r_i)\right]\Psi = E\,\Psi \qquad E = \sum_{i=1}^{N} E_i$$

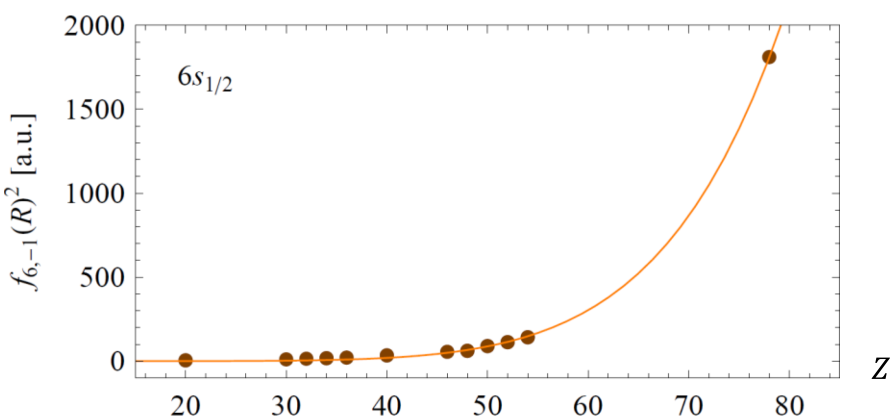
$$\Psi = \frac{1}{\sqrt{N!}}\begin{vmatrix} \psi_1(\vec{r}_1) & \cdots & \psi_1(\vec{r}_N) \\ \vdots & \ddots & \vdots \\ \psi_N(\vec{r}_1) & \cdots & \psi_N(\vec{r}_N) \end{vmatrix}$$

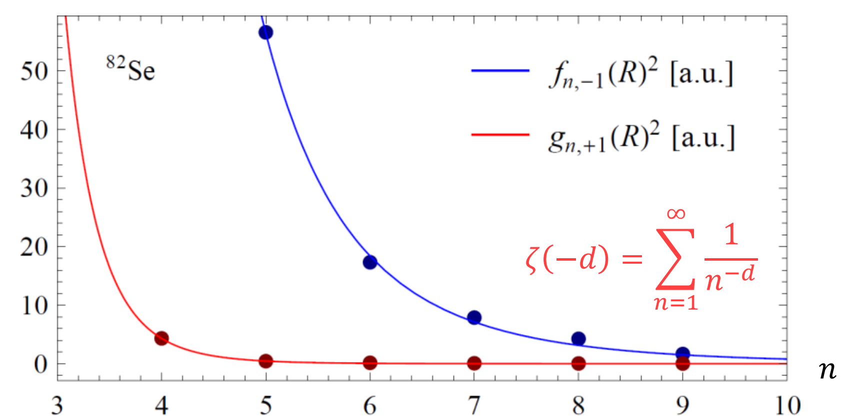


[Jönsson, Gaigalas, Bieroǹ, Froese Fischer, Grant, *Comput.Phys.Commun.* **184** (2013)]

Multiconfiguration Dirac–Hartree–Fock package GRASP2K:

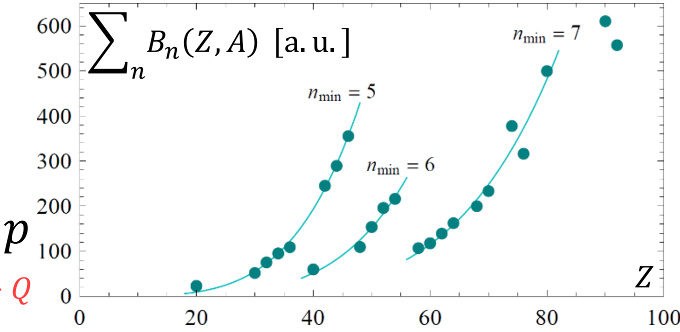
- Fit of non-convergent orbitals: $f^2_{n,-1}, g^2_{n,+1}(R) \approx aZ^b$
- Fit of orbitals beyond $n = 9$: $f^2_{n,-1}, g^2_{n,+1}(R) \approx cn^d$





Results: Phase-Space Factors & Single-Electron Spectra

$0\nu\mathrm{EP}\beta^-$ and $2\nu\mathrm{EP}\beta^-$ phase-space factors:



$$G^{0\nu\mathrm{EP}\beta}(Z,Q) = \frac{G_\beta^4\, m_e^2}{32\pi^4 R^2 \ln 2} \sum_{n=n_{\min}}^{\infty} B_n(Z,A)\, F(Z+2,E)\, E\, p$$

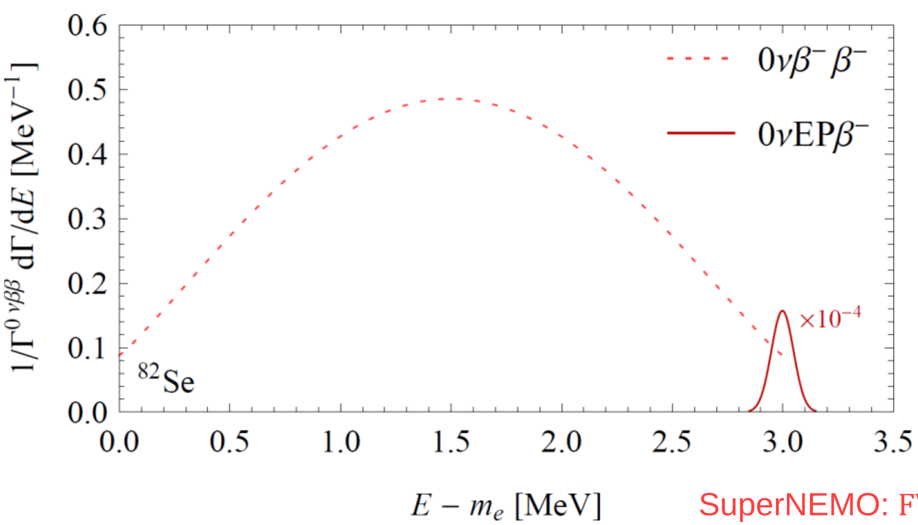
$E = m_e + Q$

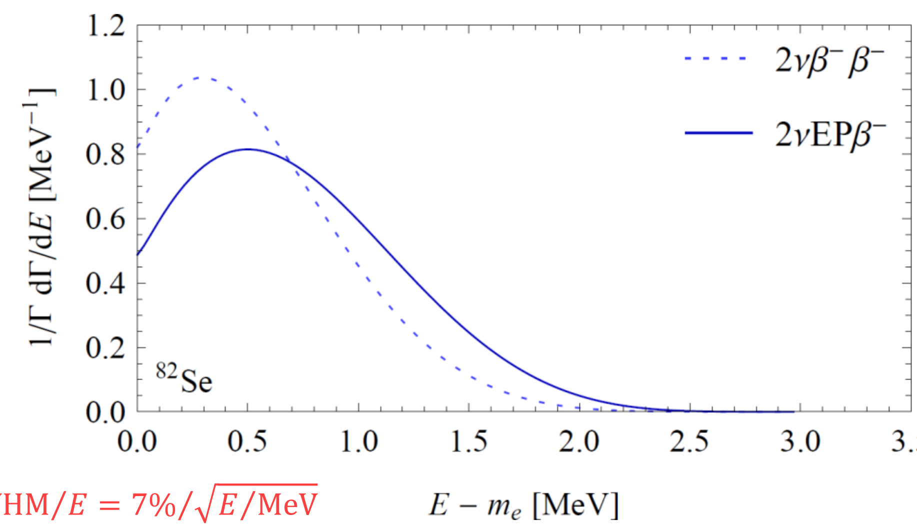
$Q = M_i - M_f - 2m_e$

$$G^{2\nu\mathrm{EP}\beta}(Z,Q) = \frac{G_\beta^4}{8\pi^6 m_e^2 \ln 2} \sum_{n=n_{\min}}^{\infty} B_n(Z,A) \int_{m_e}^{m_e+Q} \mathrm{d}E\, F(Z+2,E)\, E\, p \int_0^{m_e+Q-E} \mathrm{d}\omega_1\, \omega_1^2\, \omega_2^2$$

$\omega_2 = m_e + Q - E - \omega_1$

Single-electron spectra for ^{82}Se ($Q = 2.998$ MeV):





SuperNEMO: $\mathrm{FWHM}/E = 7\%/\sqrt{E/\mathrm{MeV}}$

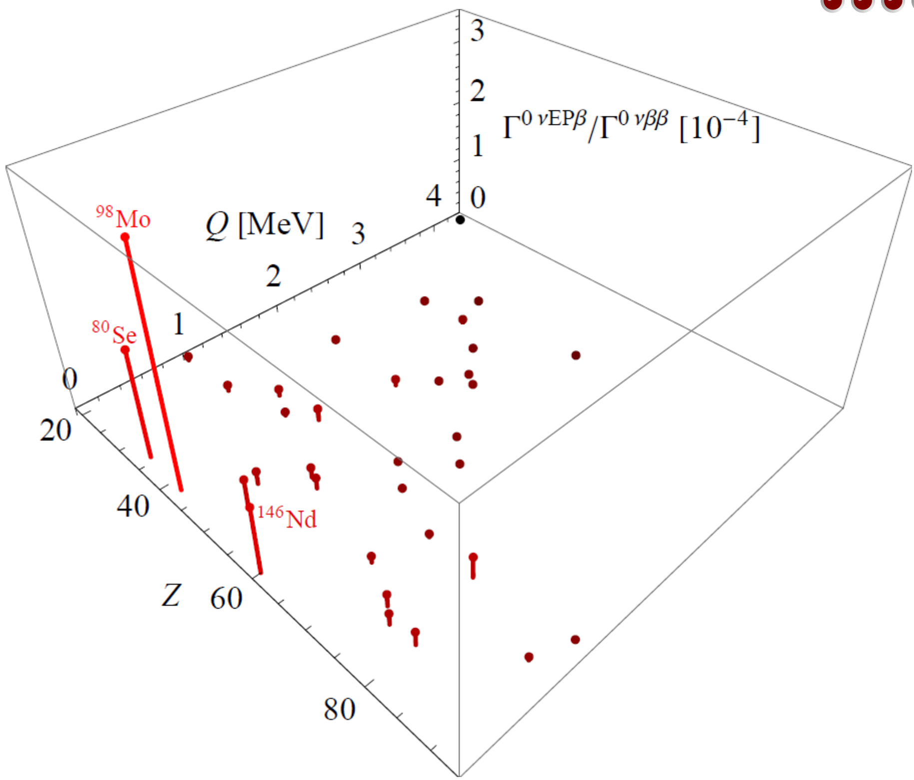
Results: Decay-Rate Ratios & Half-Lives (Table)

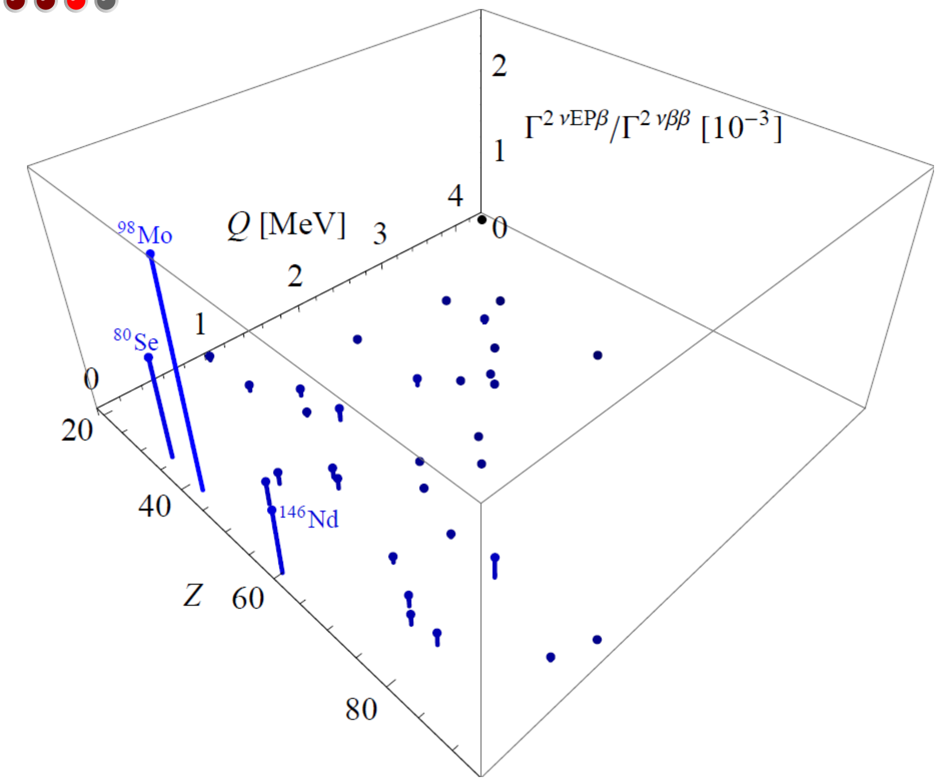
${}^{A}_{Z}X$	Q [MeV]	$\Gamma^{0\nu\mathrm{EP}\beta}/\Gamma^{0\nu\beta\beta}$	$\Gamma^{2\nu\mathrm{EP}\beta}/\Gamma^{2\nu\beta\beta}$	$T_{1/2}^{0\nu\beta\beta}$ [y]	$T_{1/2}^{0\nu\mathrm{EP}\beta}$ [y]	$T_{1/2}^{2\nu\beta\beta}$ [y]	$T_{1/2}^{2\nu\mathrm{EP}\beta}$ [y]
${}^{48}\mathrm{Ca}$	4.268	3.55×10^{-7}	3.77×10^{-6}	4.33×10^{27}	1.22×10^{34}	4.40×10^{19}	1.17×10^{25}
${}^{76}\mathrm{Ge}$	2.039	3.63×10^{-6}	3.07×10^{-5}	4.96×10^{26}	1.36×10^{32}	1.65×10^{21}	5.37×10^{25}
${}^{82}\mathrm{Se}$	2.998	1.97×10^{-6}	1.83×10^{-5}	1.39×10^{26}	7.04×10^{31}	9.20×10^{19}	5.03×10^{24}
${}^{96}\mathrm{Zr}$	3.356	7.67×10^{-7}	7.25×10^{-6}	1.89×10^{26}	2.46×10^{32}	2.30×10^{19}	3.17×10^{24}
${}^{100}\mathrm{Mo}$	3.034	3.60×10^{-6}	3.29×10^{-5}	6.22×10^{25}	1.73×10^{31}	7.10×10^{18}	2.16×10^{23}
${}^{116}\mathrm{Cd}$	2.813	1.45×10^{-6}	1.28×10^{-5}	1.03×10^{26}	7.13×10^{31}	2.87×10^{19}	2.24×10^{24}
${}^{128}\mathrm{Te}$	0.867	1.57×10^{-5}	1.09×10^{-4}	2.13×10^{27}	1.36×10^{32}	2.00×10^{24}	1.84×10^{28}
${}^{130}\mathrm{Te}$	2.528	2.68×10^{-6}	2.29×10^{-5}	1.16×10^{26}	4.33×10^{31}	6.90×10^{20}	3.01×10^{25}
${}^{136}\mathrm{Xe}$	2.458	2.85×10^{-6}	2.41×10^{-5}	3.53×10^{26}	1.24×10^{32}	2.19×10^{21}	9.09×10^{25}
${}^{150}\mathrm{Nd}$	3.371	6.29×10^{-7}	5.72×10^{-6}	4.02×10^{25}	6.39×10^{31}	8.20×10^{18}	1.43×10^{24}

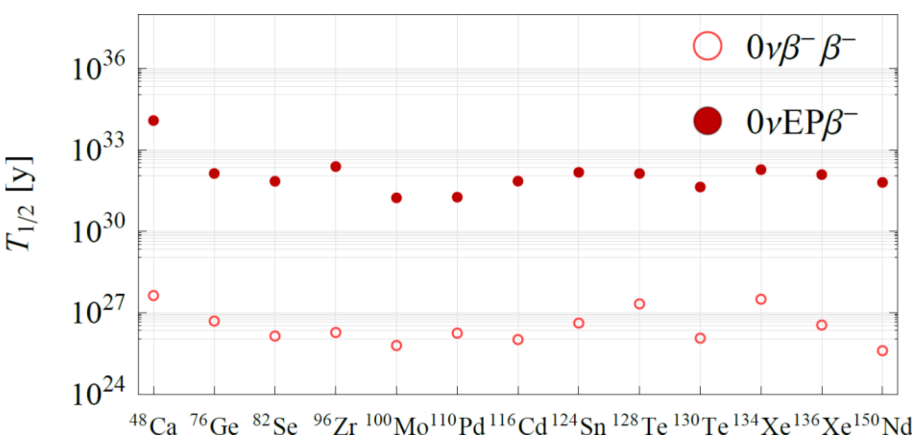
Results for g.s. $0^+ \longrightarrow 0^+$ nuclear transitions:

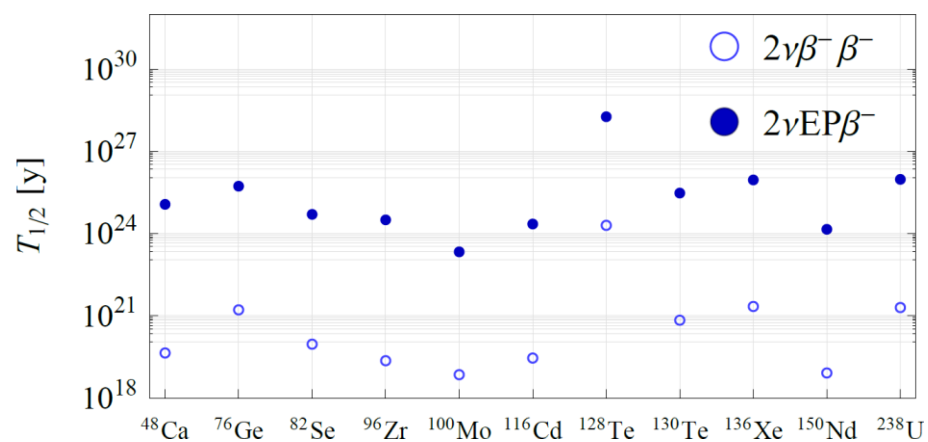
- Decay-rate ratios $\Gamma^{0\nu(2\nu)\mathrm{EP}\beta}/\Gamma^{0\nu(2\nu)\beta\beta} \approx G^{0\nu(2\nu)\mathrm{EP}\beta}/G^{0\nu(2\nu)\beta\beta}$
- Half-lives $T_{1/2}^{0\nu\beta\beta}$, $T_{1/2}^{0\nu\mathrm{EP}\beta}$ estimated assuming $g_A = 1.27$, $|M^{0\nu\beta\beta}|$ via pn-QRPA with CD-Bonn potential, $|m_{\beta\beta}| = 50$ meV
  [Šimkovic, Rodin, Faessler, Vogel, *Phys.Rev.C* **87** (2013)]
  [Fang, Faessler, Šimkovic, *Phys.Rev.C* **92** (2015)]
- Half-lives $T_{1/2}^{2\nu\mathrm{EP}\beta}$ calculated from measured $T_{1/2}^{2\nu\beta\beta}$
  [Barabash, *Nucl.Phys.A* **935** (2015)]

RESULTS: DECAY-RATE RATIOS & HALF-LIVES (PLOTS)



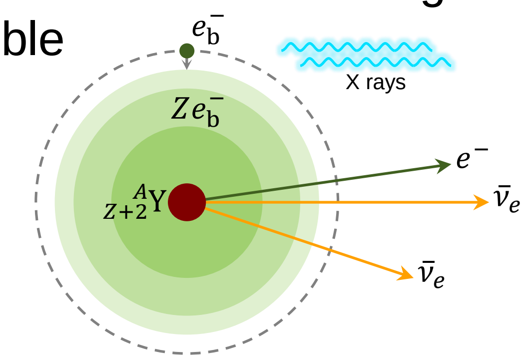


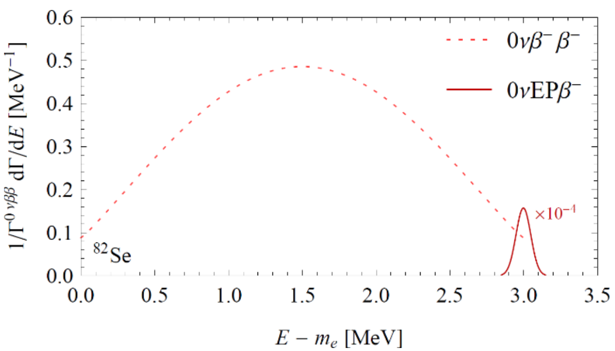


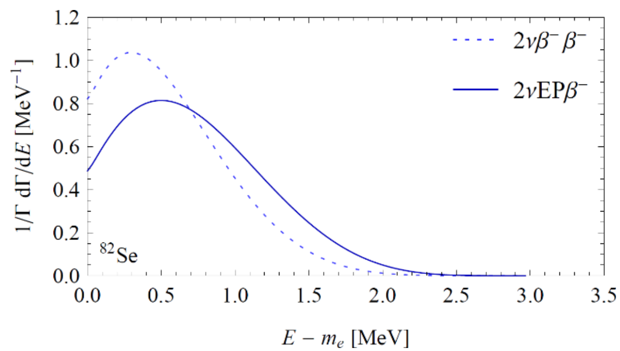


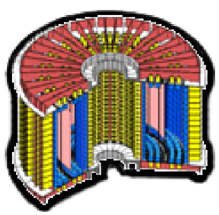
Summary:

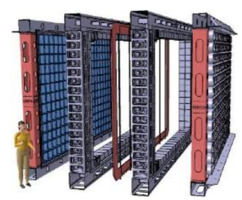
- Double-beta-decay modes $0\nu(2\nu)\mathrm{EP}\beta^-$ with Electron Placement into bound state
- Phase-space factors $G^{0\nu(2\nu)\mathrm{EP}\beta}(Z,Q)$ calculated via MCDHF package GRASP2K
- Decay-rate ratios $\Gamma^{0\nu(2\nu)\mathrm{EP}\beta}/\Gamma^{0\nu(2\nu)\beta\beta}$ decreasing rapidly with both Z and Q
- Suppression due to occupied atomic shells and shielding effect of nuclear charge
- Collective effects of crystal-lattice structure deemed negligible











Outlook:

- $0\nu\mathrm{EP}\beta^-$ strongly suppressed, but $2\nu\mathrm{EP}\beta^-$ already at $0\nu\beta^-\beta^-$ sensitivity!
- Set limits from NEMO-3 and SuperNEMO single-electron spectra with high S/B
- Study possible implications for astrophysical processes (highly-ionized plasma)
- Generalize $0\nu\mathrm{EP}\beta^-$ to various mechanisms of L-violation ($V+A$, SUSY, Majoron, …)

Summary & Outlook

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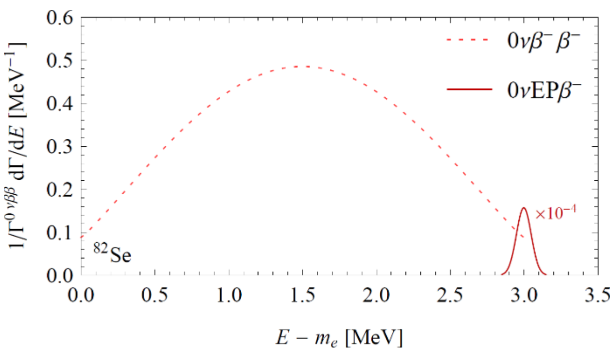

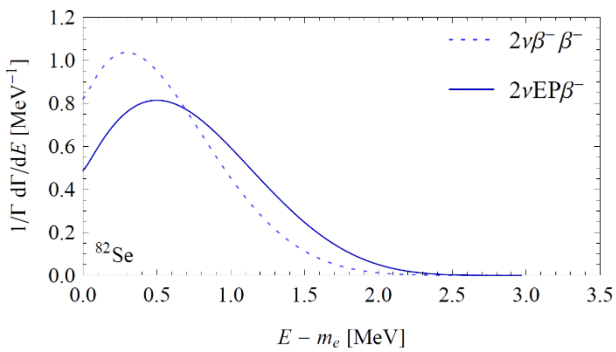

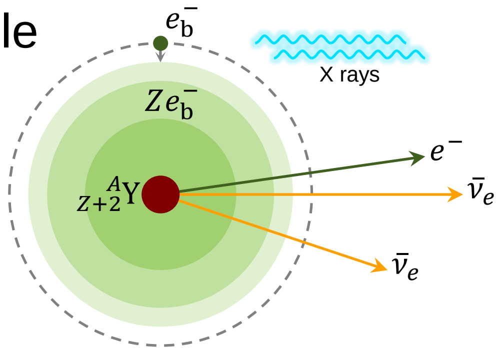

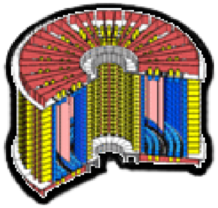

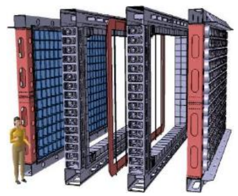

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Thank you for your attention!