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Double-Beta Decay with Emission of Single Electron

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Double-Beta Decay

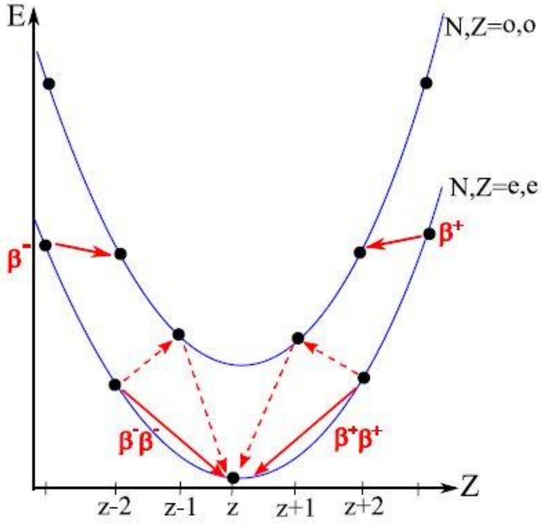
Fermi's effective QFT of beta decay is applicable at energy scales $\ll m_W$:

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

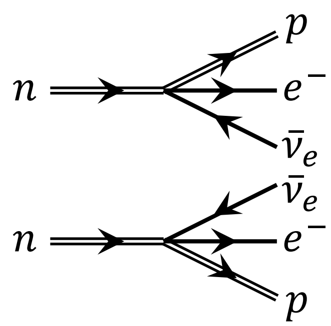
G_β: $G_\mathrm{F} \cos\theta_\mathrm{C}$

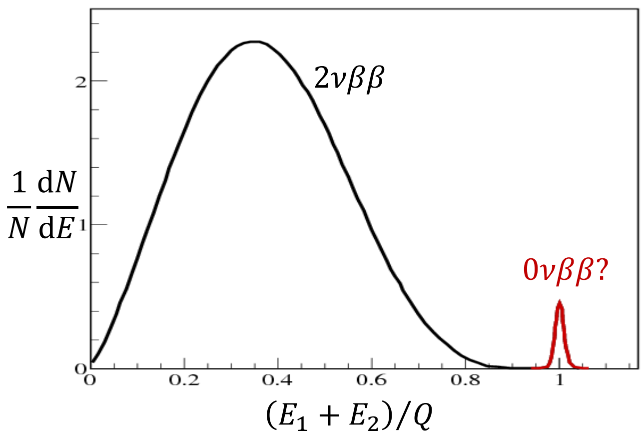
$j_\mu(x)$: $\bar{p}(x)\, \gamma_\mu\, (g_V - g_A\, \gamma^5)\, n(x)$

Two-neutrino double-beta decay $2\nu\beta^-\beta^-$ is allowed in 2nd order even if single-beta decay is forbidden or suppressed:



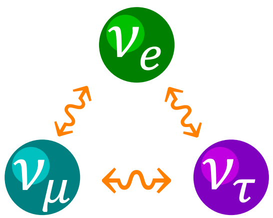
$${}^A_Z\mathrm{X} \longrightarrow {}^{\;\;A}_{Z+2}\mathrm{Y} + 2e^- + 2\bar{\nu}_e$$





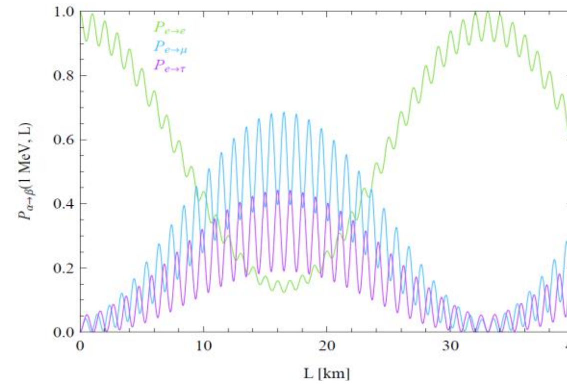
Majorana Neutrinos

Neutrino oscillations [Super-Kamiokande, 1998] imply that neutrinos are massive and mixed:

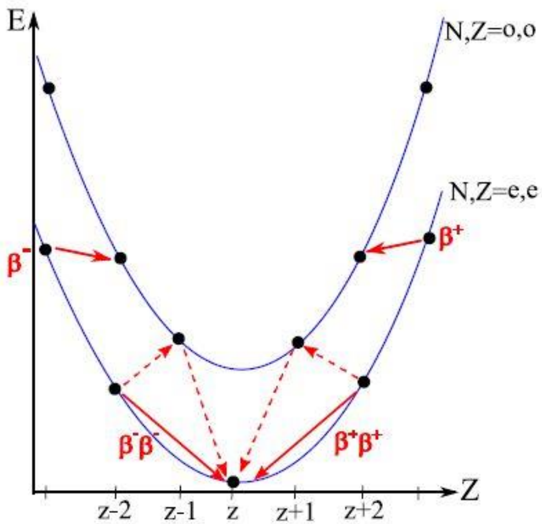


$$\nu_{\alpha L}(x) = \sum_i U_{\alpha i}\, \nu_{iL}(x)$$

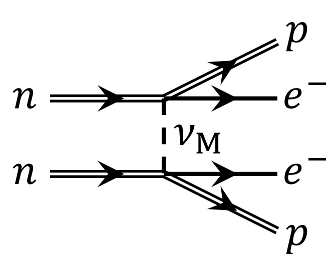
e, μ, τ $1, 2, 3$

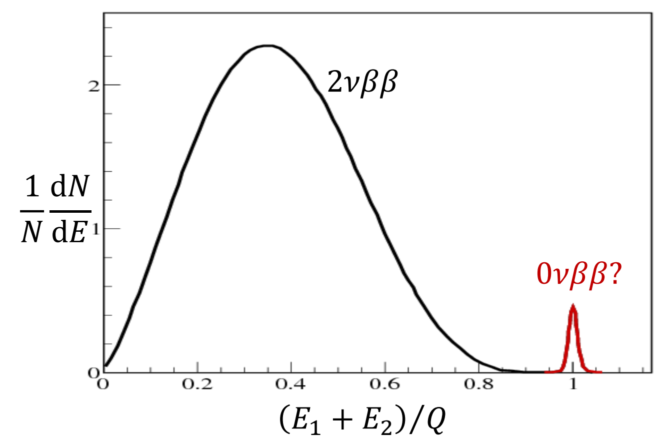


Neutrinoless double-beta decay $0\nu\beta^-\beta^-$ ($\Delta L = 2$) is allowed if massive neutrinos are Majorana fermions ($\nu_\alpha = \bar{\nu}_\alpha$):



$${}^{A}_{Z}\mathrm{X} \longrightarrow {}_{Z+2}^{\;\;A}\mathrm{Y} + 2e^-$$





Bound-State Beta Decay

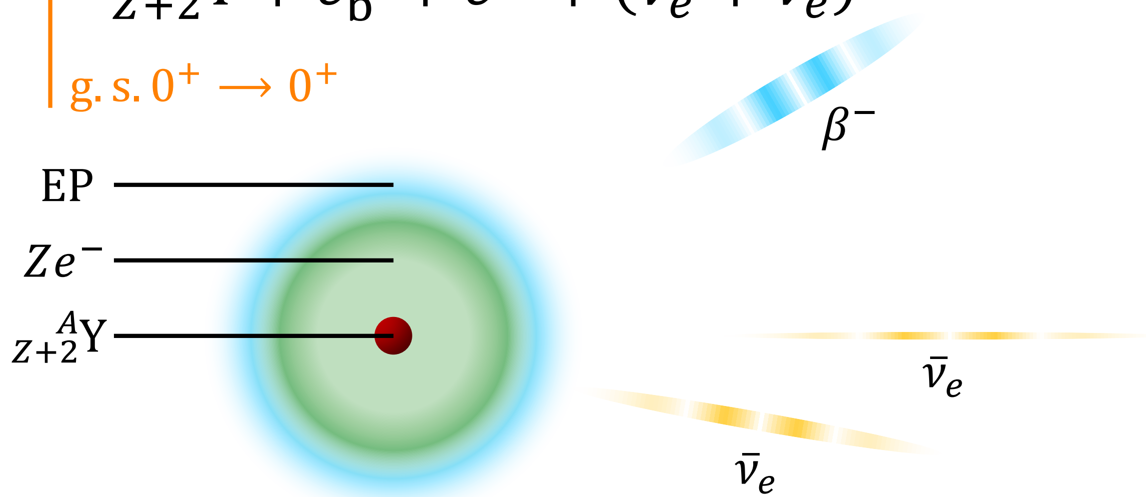
[Jung et al. (GSI), 1992] observed beta decay of ${}^{163}_{66}\mathrm{Dy}^{66+}$ ions with electron production (EP) in K or L shells: $T_{1/2}^{\mathrm{EP}} = 47\ \mathrm{d}$

Nucleosynthesis?

Bound-state double-beta decay $0\nu\mathrm{EP}\beta^-$ ($2\nu\mathrm{EP}\beta^-$) with EP in available $s_{1/2}$ or $p_{1/2}$ subshell of daughter 2+ ion:

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

$\mathrm{g.s.}\ 0^{+} \longrightarrow 0^{+}$



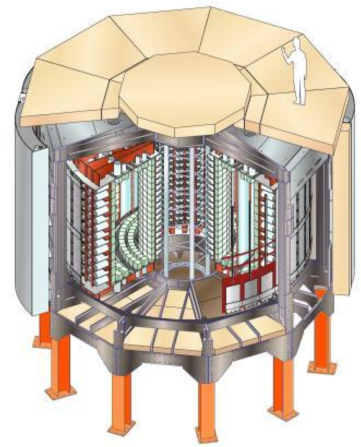
Search for possible manifestation in single-electron spectra…

Neutrino Ettore Majorana Observatory

Tracking & calorimetry double-beta-decay experiments at LSM:

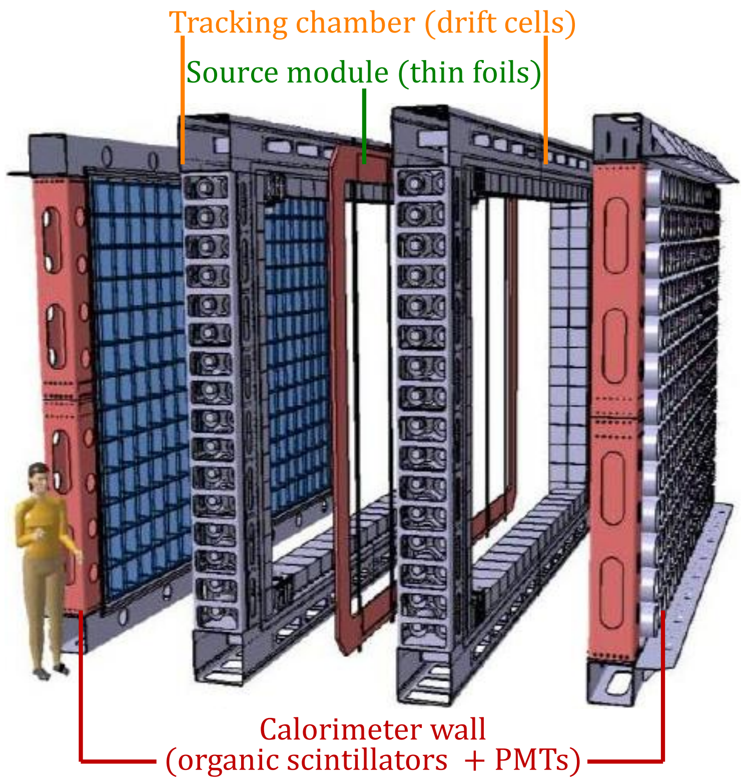
NEMO 3 (2003 – 2011):

- $^{100}\mathrm{Mo}$ (7 kg), $^{82}\mathrm{Se}$ (1 kg), etc.
- 700,000 events for $^{100}\mathrm{Mo}$ during 3.49 y of exposure



SuperNEMO (under construction):

- $^{82}\mathrm{Se}$, $^{150}\mathrm{Nd}$ or $^{48}\mathrm{Ca}$ $(20 \times 5\ \mathrm{kg})$
- $\mathrm{FWHM}/E = 7\%/\sqrt{E/\mathrm{MeV}}$



Access to single-electron spectra means potential to observe or set limits on $0\nu\mathrm{EP}\beta^-$ and $2\nu\mathrm{EP}\beta^-$!

Relativistic Electron Wave Functions

Solution to Dirac equation with Coulomb potential:

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

κ: $(l-j)(2j+1)$; μ: $-j,\dots,+j$

Continuous spectrum assumes dominant term from partial-wave expansion:

$$\psi^s_{s_{1/2}}(\vec{p},\vec{r}) = \begin{pmatrix} f_{-1}(E,r)\,\chi^s \\ g_{+1}(E,r)\,(\vec{\sigma}\cdot\hat{p})\,\chi^s \end{pmatrix}$$

E: $\sqrt{\vec{p}^2 + m_e^2}$

Relativistic $s_{1/2}$ wave reduces to Fermi function:

$$F(Z,E) = f^2_{-1}(E,R) + g^2_{+1}(E,R)$$

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

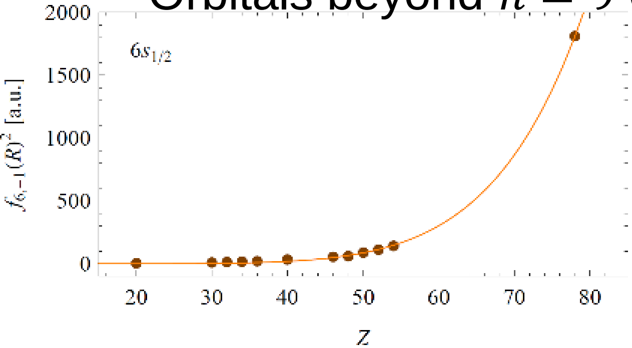
Bound-state Fermi function:

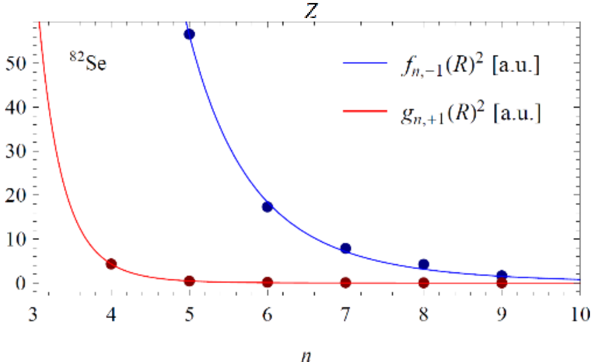
$$B_n(Z,A) = f_{n,-1}^2(R) + g_{n,+1}^2(R) \quad \longrightarrow |\psi_{nlm}(R)|^2$$

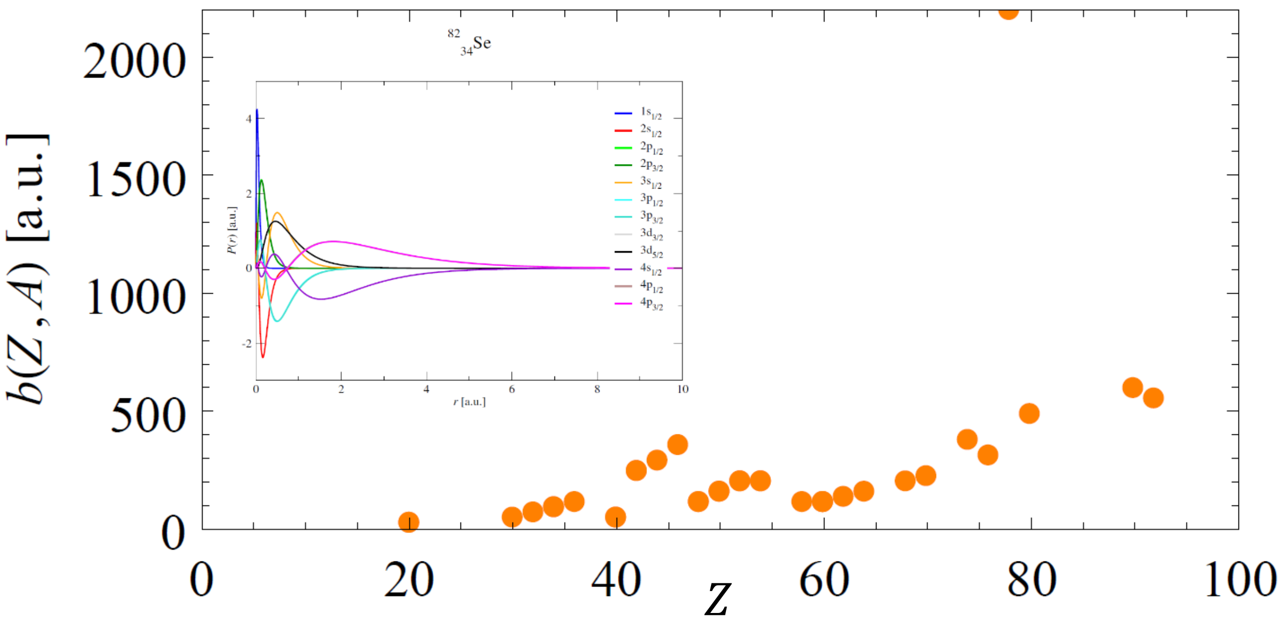
($f_{n,-1}$: $ns_{1/2}$; $g_{n,+1}$: $np_{1/2}$)

Discrete Fermi "integral" $b(Z,A) = \sum_{n=n_{\min}}^{\infty} B_n(Z,A)$ calculated via multiconfig. Dirac–Hartree–Fock package GRASP2K:

- Non-convergent orbitals replaced by fit: aZ^b $\longrightarrow$ [Niskanen *et al.*, J. Chem. Phys. **135** (2011)]
- Orbitals beyond $n = 9$ estimated by fit: cn^d $\longrightarrow \zeta(-d)$ (5%)







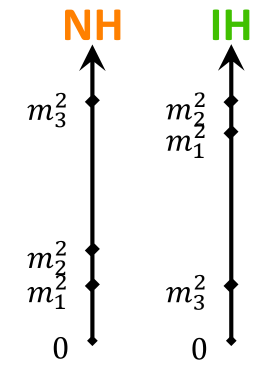
$0\nu\beta^-\beta^-$ and $2\nu\beta^-\beta^-$ Half-Lives

Inverse $0\nu\beta^-\beta^-$ half-life:

$\Gamma = \ln 2 / T_{1/2}$

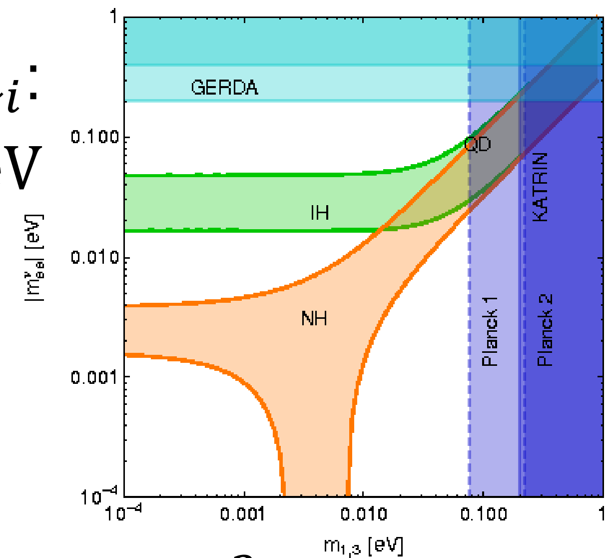
$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = g_A^4 \, G^{0\nu\beta\beta}(Z,Q) \left|M^{0\nu\beta\beta}\right|^2 \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

g_A: 1.269 (unquenched)



Effective Majorana ν mass $m_{\beta\beta} = \sum_i U_{ei}^2 \, m_i$:

- KamLAND-Zen (^{136}Xe): $|m_{\beta\beta}| < 165$ meV
- Inverted hierarchy: $|m_{\beta\beta}| \sim 50$ meV



Inverse $2\nu\beta^-\beta^-$ half-life:

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

Standard approximations: $M^{0\nu\mathrm{EP}\beta} \approx M^{0\nu\beta\beta}$, $M^{2\nu\mathrm{EP}\beta} \approx M^{2\nu\beta\beta}$

$0\nu\mathrm{EP}\beta^-$ Phase-Space Factor

$0\nu\beta^-\beta^-$ phase-space factor:

$$G^{0\nu\beta\beta} = \frac{G_\beta^4 \, m_e^2}{32\pi^5 R^2 \ln 2} \int_{m_e}^{m_e+Q} \mathrm{d}E_1 \, F(Z+2, E_1) \, E_1 \, p_1 \, F(Z+2, E_2) \, E_2 \, p_2$$

$0\nu EP\beta^-$ phase-space factor:

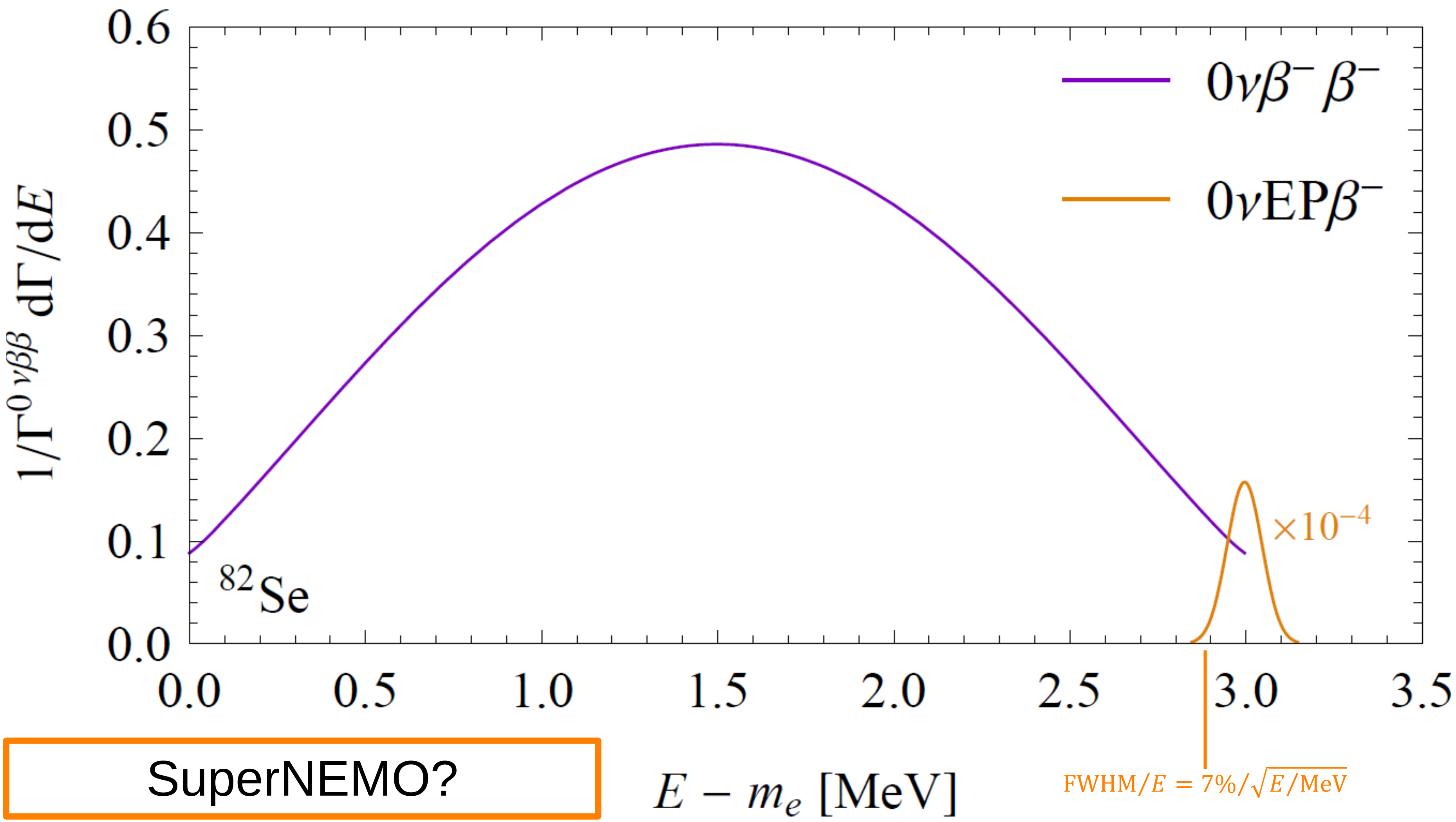
$$G^{0\nu\mathrm{EP}\beta} = \frac{G_\beta^4 \, m_e^2}{32\pi^4 R^2 \ln 2} \sum_{n=n_{\mathrm{min}}}^{\infty} B_n(Z, A) \, F(Z+2, E) \, E \, p$$

Kinematics:

- Neglected e_b^- binding energies ($\sim 1\ \mathrm{eV}$) and nuclear recoil
- E_2 (continuous) and $E = m_e + Q$ from energy conservation

$0\nu\mathrm{EP}\beta^-$ Single-Electron Spectrum ($^{82}\mathrm{Se}$)

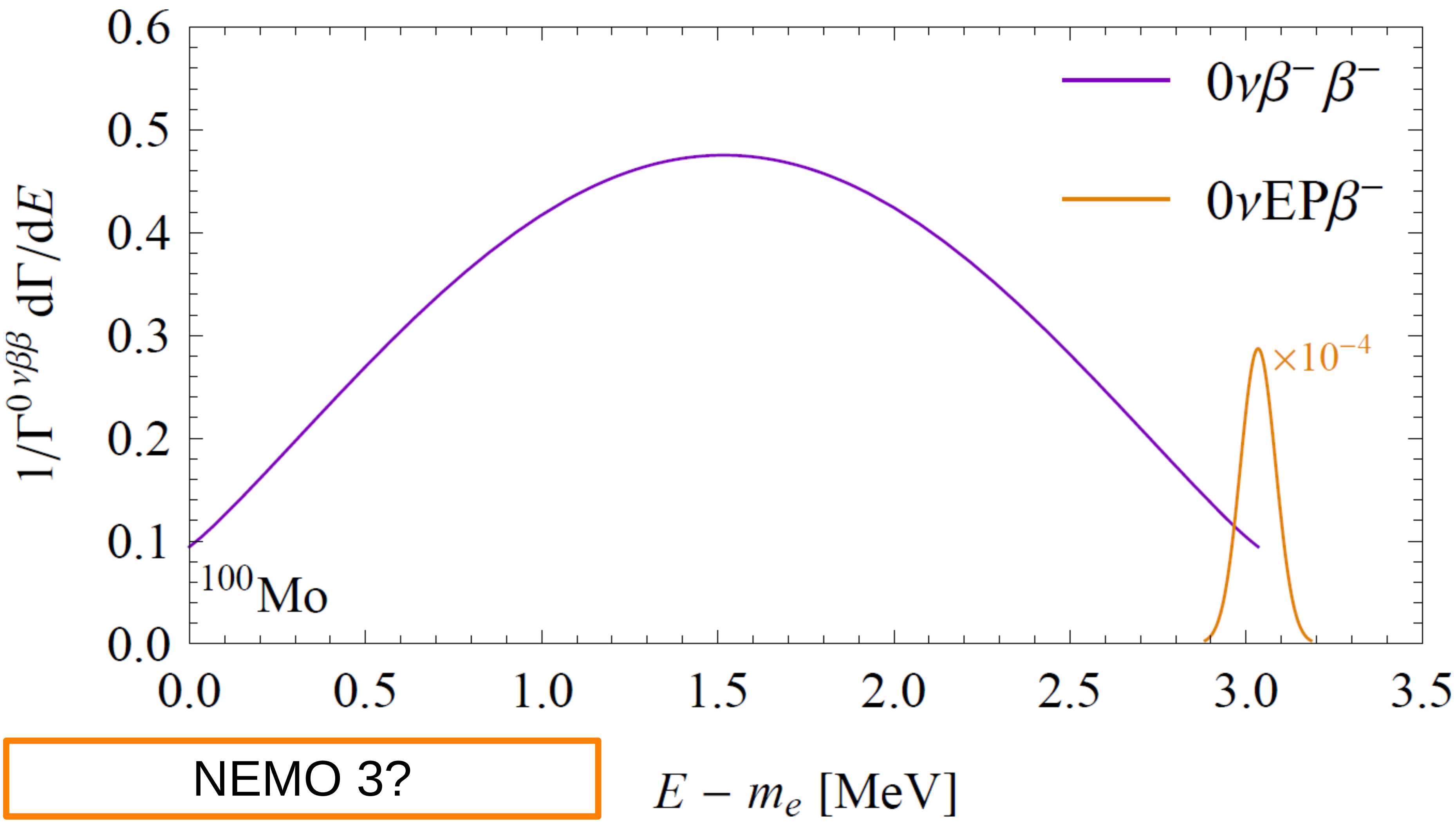
$0\nu\beta^-\beta^-$ and $0\nu\mathrm{EP}\beta^-$ single-electron spectra $1/\Gamma^{0\nu\beta\beta}\,\mathrm{d}\Gamma/\mathrm{d}E$ vs. electron kinetic energy $E - m_e$ for $^{82}\mathrm{Se}$ ($Q = 2.996$ MeV):



SuperNEMO?

$0\nu\mathrm{EP}\beta^-$ Single-Electron Spectrum ($^{100}\mathrm{Mo}$)

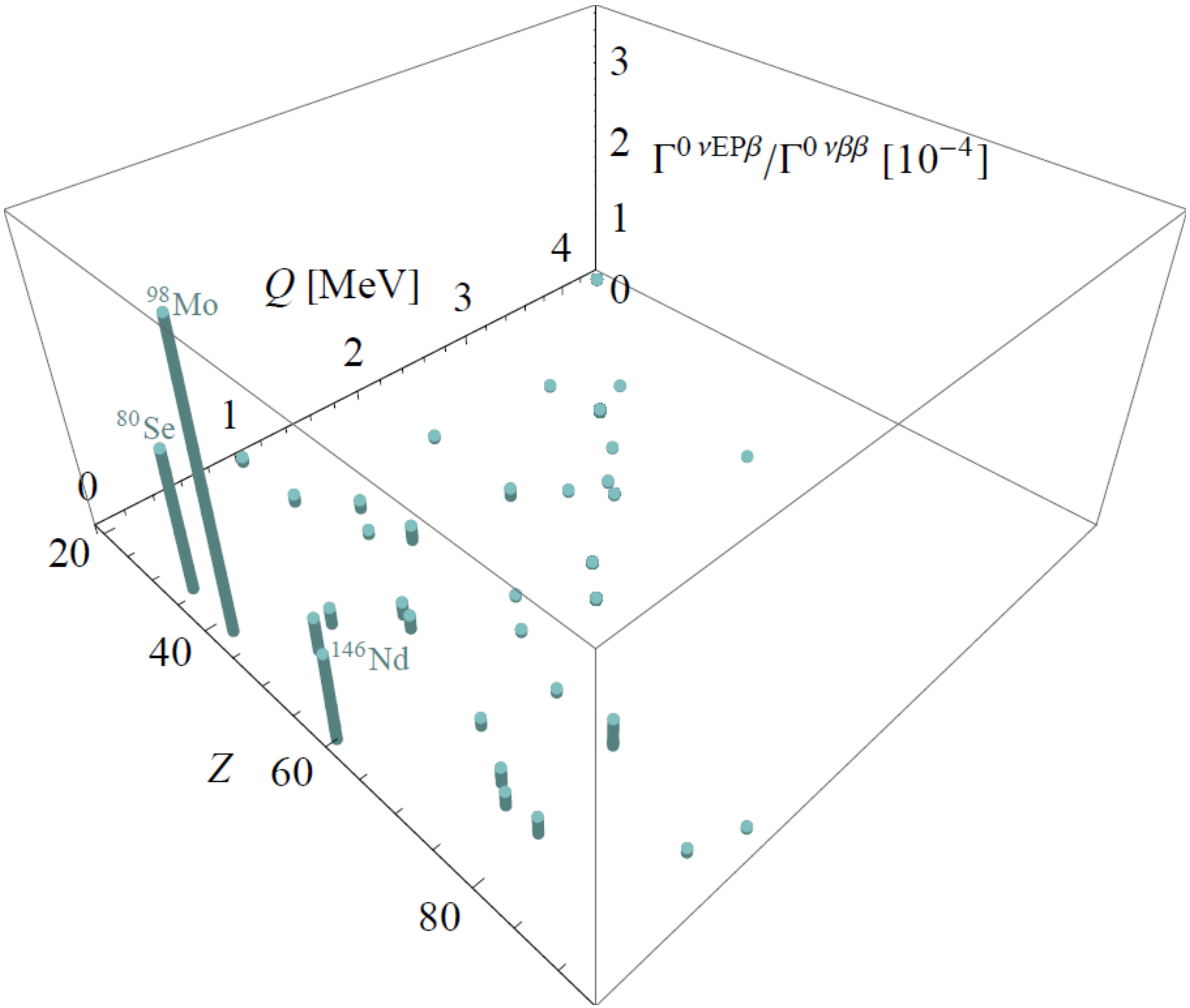
$0\nu\beta^-\beta^-$ and $0\nu\mathrm{EP}\beta^-$ single-electron spectra $1/\Gamma^{0\nu\beta\beta}\,\mathrm{d}\Gamma/\mathrm{d}E$ vs. electron kinetic energy $E - m_e$ for $^{100}\mathrm{Mo}$ ($Q = 3.034$ MeV):



NEMO 3?

Decay-Rate Ratios $\Gamma^{0\nu\text{EP}\beta}/\Gamma^{0\nu\beta\beta}$

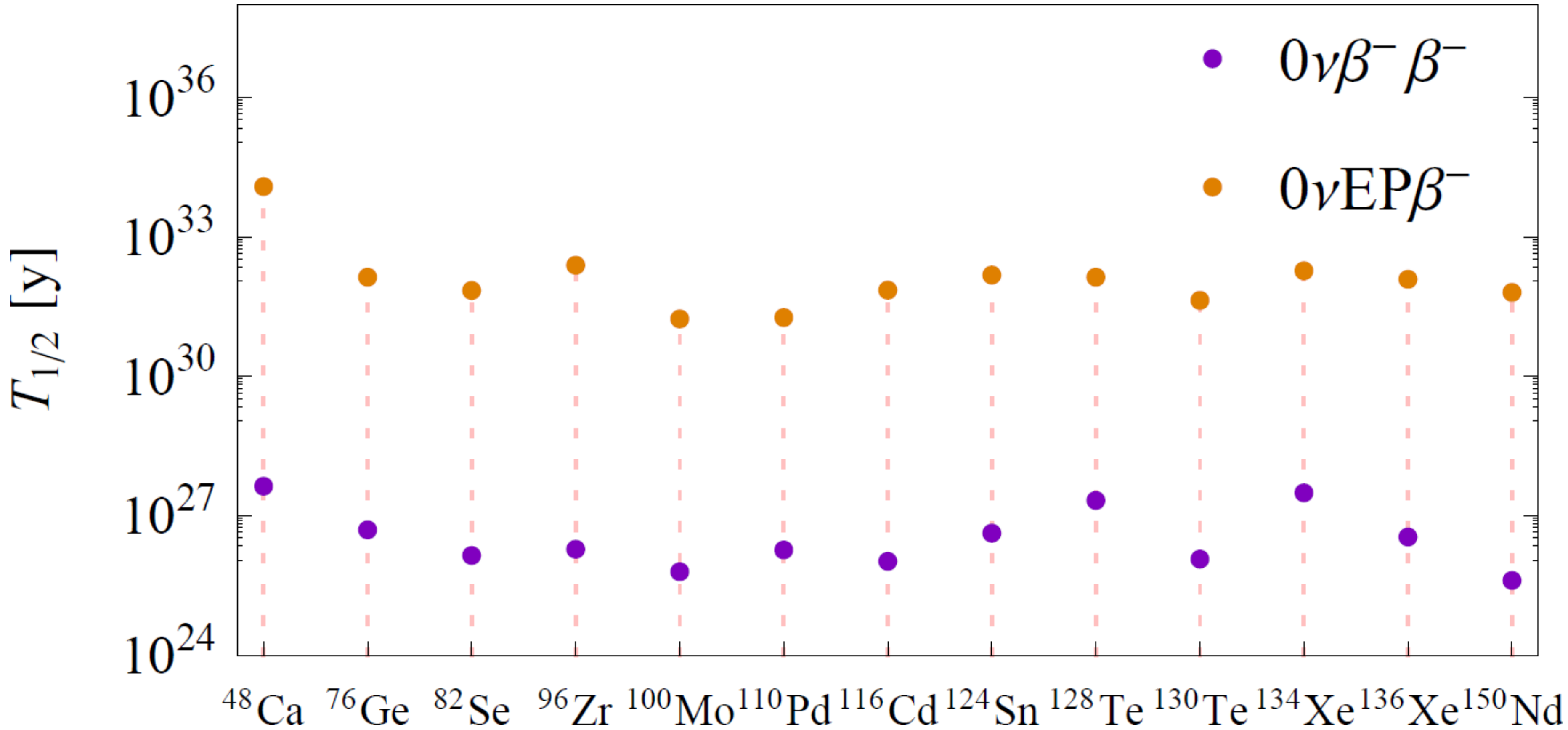
Decay-rate ratios $\Gamma^{0\nu\text{EP}\beta}/\Gamma^{0\nu\beta\beta} = G^{0\nu\text{EP}\beta}/G^{0\nu\beta\beta}$ vs. parent atomic number Z and Q value for all 35 $\beta^-\beta^-$ isotopes:



$0\nu\mathrm{EP}\beta^-$ Half-Lives

$0\nu\beta^-\beta^-$ and $0\nu\mathrm{EP}\beta^-$ half-lives $T_{1/2}^{0\nu\beta\beta}$ and $T_{1/2}^{0\nu\mathrm{EP}\beta}$ estimated for $\beta^-\beta^-$ isotopes with known $|M^{0\nu\beta\beta}|$, assuming unquenched $g_A = 1.269$ and $|m_{\beta\beta}| = 50\ \mathrm{meV}$:

pn−QRPA w. CD−Bonn potential
[Šimkovic *et al.*, Phys. Rev. C**87** (2013)]
[D. −L. Fang *et al.*, Phys. Rev. C**92** (2015)]



$2\nu\mathrm{EP}\beta^-$ Phase-Space Factor

$2\nu\beta^-\beta^-$ phase-space factor:

$$G^{2\nu\beta\beta} = \frac{G_\beta^4}{8\pi^7 m_e^2 \ln 2} \times \int_{m_e}^{m_e+Q} \mathrm{d}E_1\, F(Z+2,E_1)\, E_1\, p_1 \int_{m_e}^{2m_e+Q-E_1} \mathrm{d}E_2\, F(Z+2,E_2)\, E_2\, p_2 \int_0^{2m_e+Q-E_1-E_2} \mathrm{d}\omega_1\, \omega_1^2\, \omega_2^2$$

$2\nu\mathrm{EP}\beta^-$ phase-space factor:

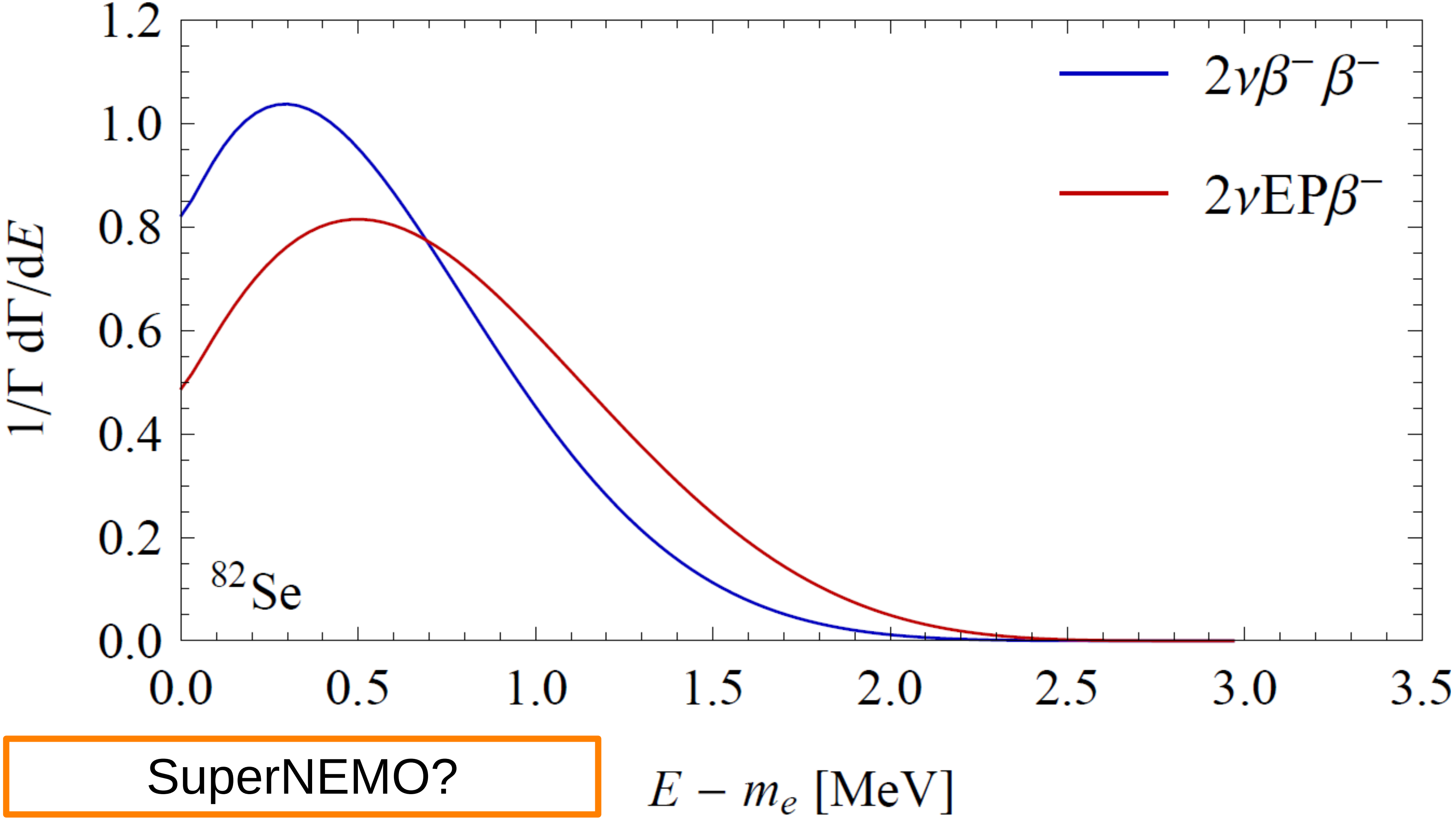
$$G^{2\nu\mathrm{EP}\beta} = \frac{G_\beta^4}{8\pi^6 m_e^2 \ln 2} \sum_{n=n_{\min}}^{\infty} B_n(Z,A) \int_{m_e}^{m_e+Q} \mathrm{d}E\, F(Z+2,E)\, E\, p \int_0^{m_e+Q-E} \mathrm{d}\omega_1\, \omega_1^2\, \omega_2^2$$

Kinematics:

- Neglected e_b^- binding energies ($\sim 1\ \mathrm{eV}$) and nuclear recoil
- Second-neutrino energy ω_2 from energy conservation

$2\nu\mathrm{EP}\beta^-$ Single-Electron Spectrum ($^{82}\mathrm{Se}$)

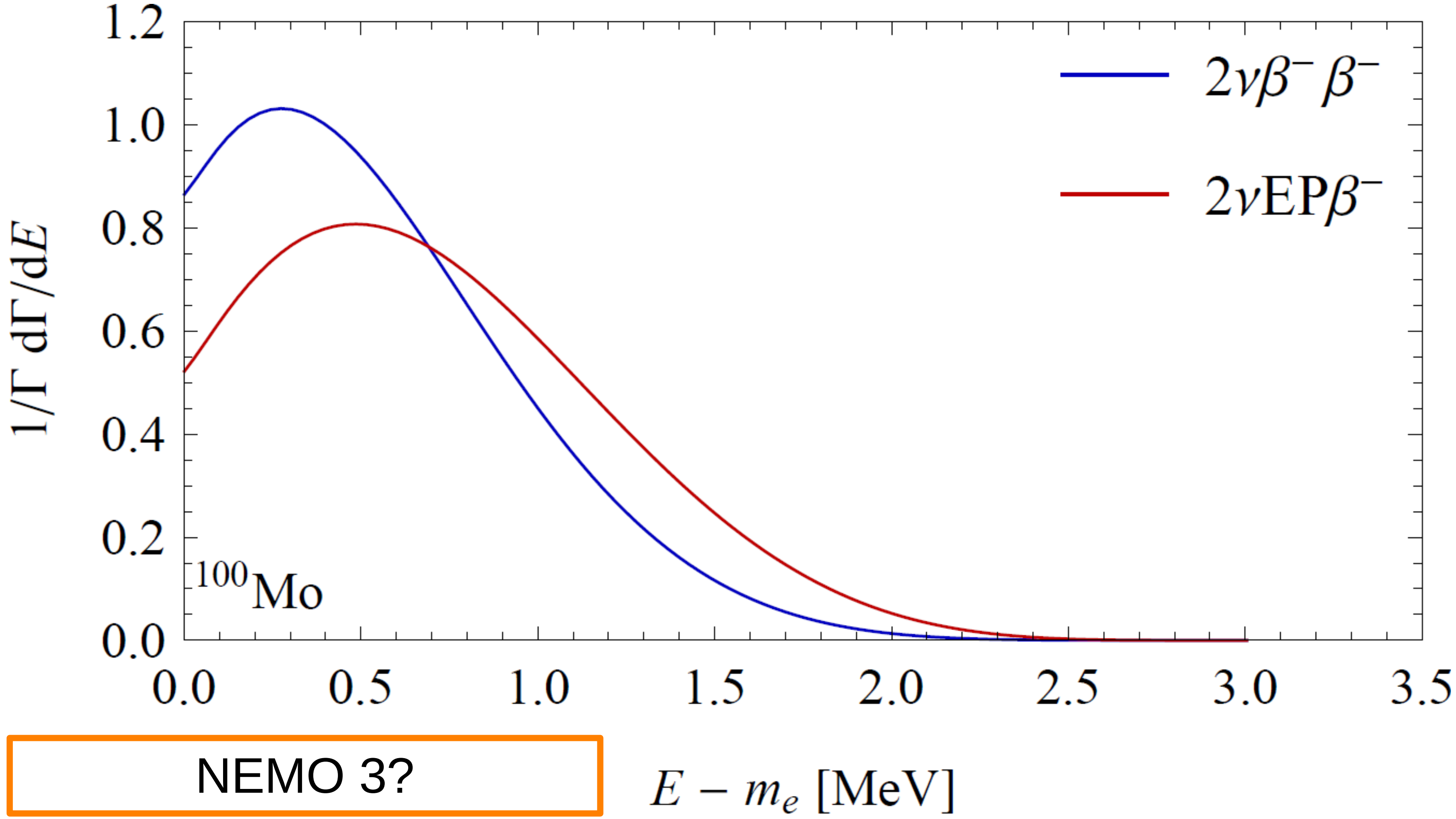
$2\nu\beta^-\beta^-$ and $2\nu\mathrm{EP}\beta^-$ single-electron spectra $1/\Gamma\,\mathrm{d}\Gamma/\mathrm{d}E$ vs. electron kinetic energy $E - m_e$ for $^{82}\mathrm{Se}$ ($Q = 2.996\ \mathrm{MeV}$):



SuperNEMO?

$2\nu\mathrm{EP}\beta^-$ Single-Electron Spectrum ($^{100}\mathrm{Mo}$)

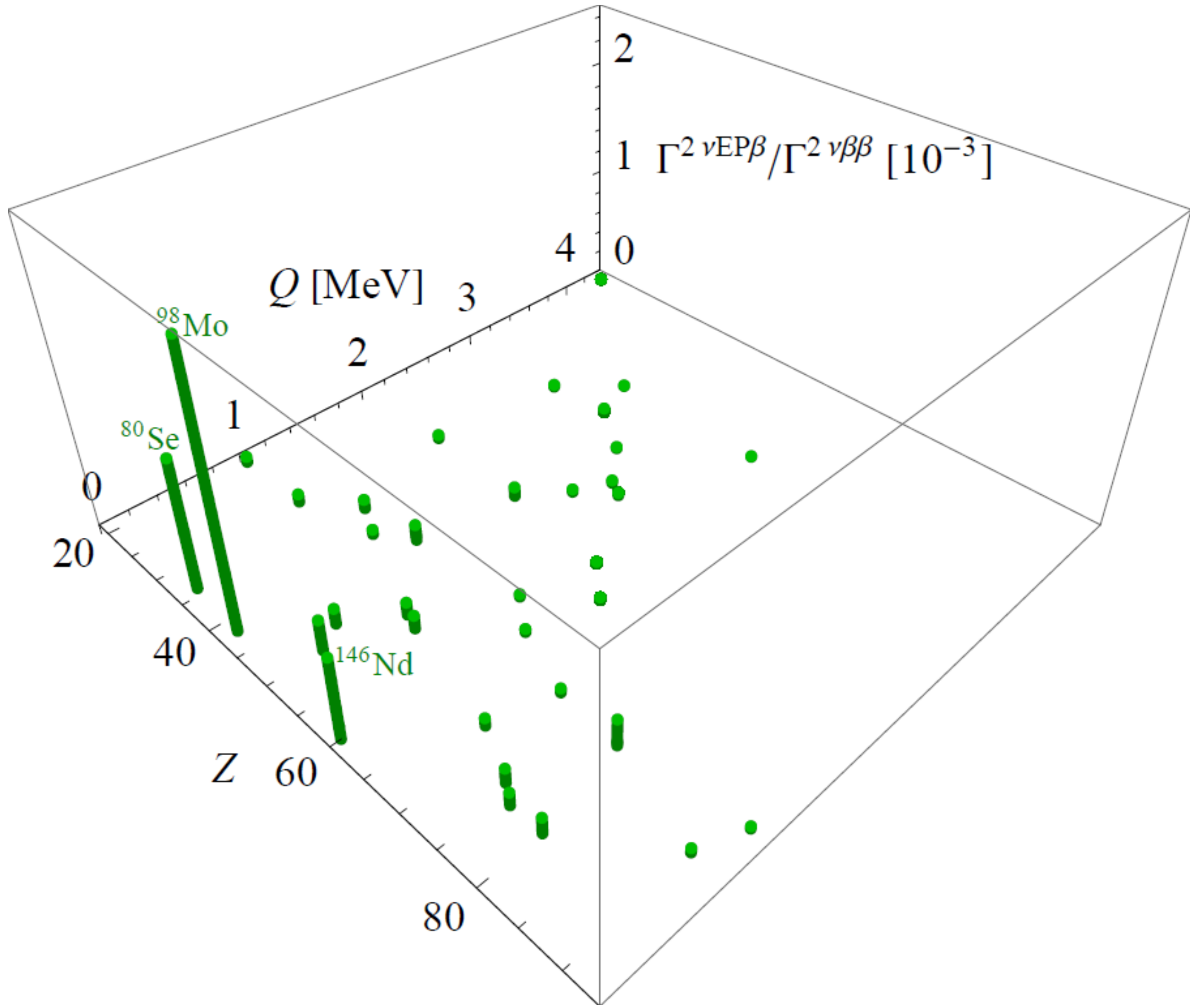
$2\nu\beta^-\beta^-$ and $2\nu\mathrm{EP}\beta^-$ single-electron spectra $1/\Gamma\,\mathrm{d}\Gamma/\mathrm{d}E$ vs. electron kinetic energy $E - m_e$ for $^{100}\mathrm{Mo}$ ($Q = 3.034\,\mathrm{MeV}$):



NEMO 3?

Decay-Rate Ratios $\Gamma^{2\nu\mathrm{EP}\beta}/\Gamma^{2\nu\beta\beta}$

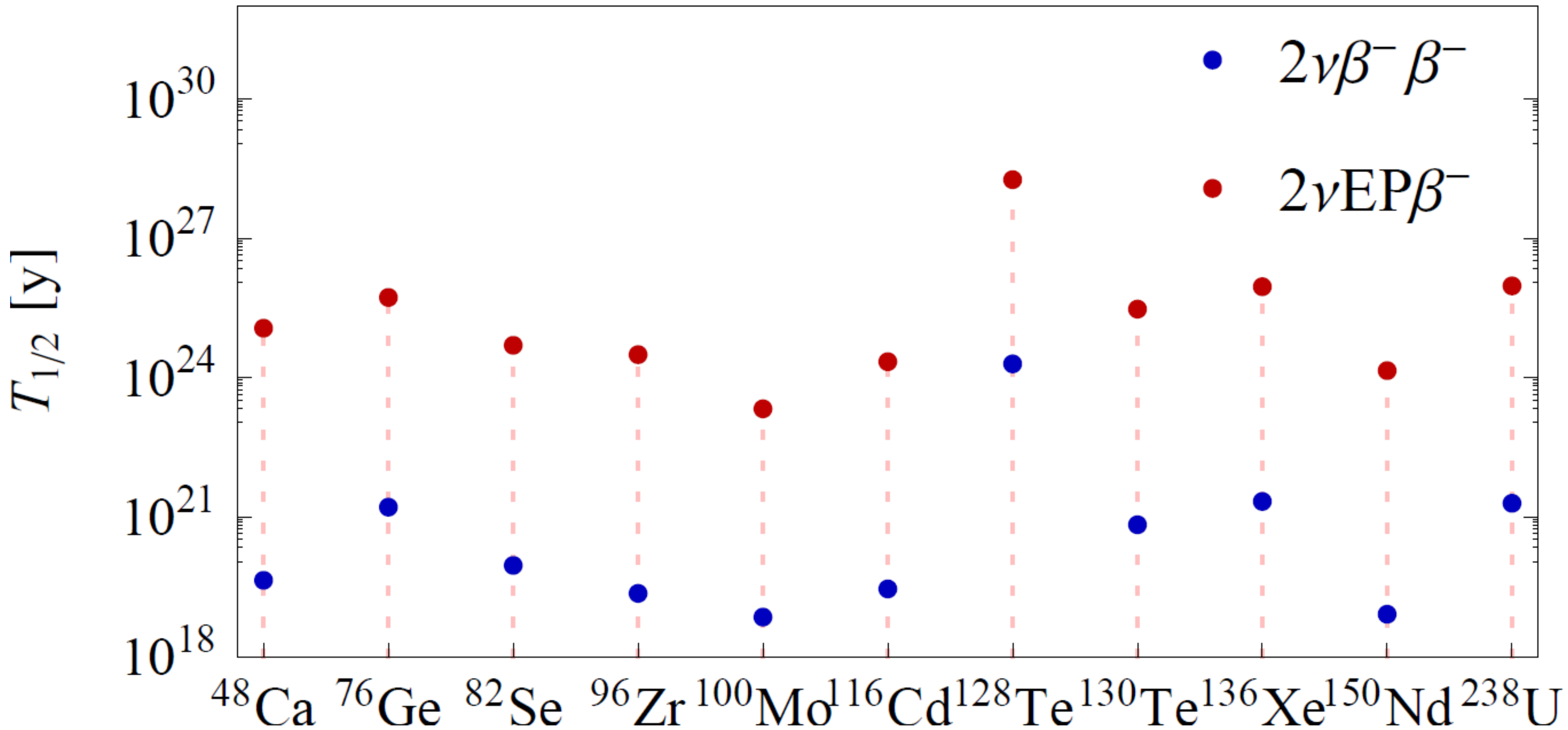
Decay-rate ratios $\Gamma^{2\nu\mathrm{EP}\beta}/\Gamma^{2\nu\beta\beta} = G^{2\nu\mathrm{EP}\beta}/G^{2\nu\beta\beta}$ vs. parent atomic number Z and Q value for all 35 $\beta^-\beta^-$ isotopes:



$2\nu\mathrm{EP}\beta^-$ Half-Lives

$2\nu\beta^-\beta^-$ and $2\nu\mathrm{EP}\beta^-$ half-lives $T_{1/2}^{2\nu\beta\beta}$ and $T_{1/2}^{2\nu\mathrm{EP}\beta}$ calculated for $\beta^-\beta^-$ isotopes observed experimentally, assuming unquenched $g_A = 1.269$:

[Barabash, Nucl. Phys. A**935** (2015)]



Summary & Outlook

- Single-electron modes $0\nu\mathrm{EP}\beta^-$ and $2\nu\mathrm{EP}\beta^-$ of double-beta decay with electron production in $s_{1/2}$ or $\mathrm{p}_{1/2}$ bound state
- Evaluation of phase-space factors, half-lives and single-electron spectra via MCDHF package GRASP2K
- Suppression due to presence of other electrons in inner atomic shells and shielding effect of nuclear charge
- $0\nu\mathrm{EP}\beta^-$ unlikely to be observed in future experiments; $2\nu\mathrm{EP}\beta^-$ as background process for single-electron spectra
- Reassessment of NEMO 3 ($^{100}\mathrm{Mo}$) data could reveal slight deformations of measured spectra; more stringent limits to be set by SuperNEMO ($^{82}\mathrm{Se}$)
- Generalization of $0\nu\mathrm{EP}\beta^-$ to left-right symmetric theories, heavy-neutrino exchange, Majoron models, etc.

Thank you for your attention!

Backup 1: Decay-Rate Ratios Table

${}^{A}_{Z}X$	Q [MeV]	$\Gamma^{0\nu EP\beta}/\Gamma^{0\nu\beta\beta}$	$\Gamma^{2\nu EP\beta}/\Gamma^{2\nu\beta\beta}$	${}^{A}_{Z}X$	Q [MeV]	$\Gamma^{0\nu EP\beta}/\Gamma^{0\nu\beta\beta}$	$\Gamma^{2\nu EP\beta}/\Gamma^{2\nu\beta\beta}$
${}^{46}_{20}Ca$	0.990	6.29×10^{-6}	4.83×10^{-5}	${}^{130}_{52}Te$	2.529	2.68×10^{-6}	2.29×10^{-5}
${}^{48}_{20}Ca$	4.272	3.55×10^{-7}	3.76×10^{-6}	${}^{134}_{54}Xe$	0.830	1.66×10^{-5}	1.15×10^{-4}
${}^{70}_{30}Zn$	1.001	9.24×10^{-6}	6.81×10^{-5}	${}^{136}_{54}Xe$	2.468	2.83×10^{-6}	2.39×10^{-5}
${}^{76}_{32}Ge$	2.039	3.63×10^{-6}	3.07×10^{-5}	${}^{142}_{58}Ce$	1.417	3.03×10^{-6}	2.25×10^{-5}
${}^{80}_{34}Se$	0.134	1.66×10^{-4}	1.11×10^{-3}	${}^{146}_{60}Nd$	0.070	1.01×10^{-4}	6.90×10^{-4}
${}^{82}_{34}Se$	2.996	1.97×10^{-6}	1.83×10^{-5}	${}^{148}_{60}Nd$	1.929	1.80×10^{-6}	1.42×10^{-5}
${}^{86}_{36}Kr$	1.256	1.05×10^{-5}	7.91×10^{-5}	${}^{150}_{60}Nd$	3.368	6.30×10^{-7}	5.73×10^{-6}
${}^{94}_{40}Zr$	1.144	5.58×10^{-6}	4.09×10^{-5}	${}^{154}_{62}Sm$	1.251	3.90×10^{-6}	2.83×10^{-5}
${}^{96}_{40}Zr$	3.350	7.70×10^{-7}	7.28×10^{-6}	${}^{160}_{64}Gd$	1.730	2.44×10^{-6}	1.88×10^{-5}
${}^{98}_{42}Mo$	0.112	3.40×10^{-4}	2.29×10^{-3}	${}^{170}_{68}Er$	0.654	9.87×10^{-6}	6.68×10^{-5}
${}^{100}_{42}Mo$	3.034	3.60×10^{-6}	3.29×10^{-5}	${}^{176}_{70}Yb$	1.087	5.21×10^{-6}	3.69×10^{-5}
${}^{104}_{44}Ru$	1.300	1.85×10^{-5}	1.38×10^{-4}	${}^{186}_{74}W$	0.488	1.87×10^{-5}	1.25×10^{-4}
${}^{110}_{46}Pd$	2.000	9.89×10^{-6}	8.05×10^{-5}	${}^{192}_{76}Os$	0.414	1.68×10^{-5}	1.12×10^{-4}
${}^{114}_{48}Cd$	0.537	2.00×10^{-5}	1.34×10^{-4}	${}^{198}_{78}Pt$	1.047	3.24×10^{-5}	2.28×10^{-4}
${}^{116}_{48}Cd$	2.805	1.46×10^{-6}	1.29×10^{-5}	${}^{204}_{80}Hg$	0.416	2.05×10^{-5}	1.38×10^{-4}
${}^{122}_{50}Sn$	0.366	4.01×10^{-5}	2.66×10^{-4}	${}^{232}_{90}Th$	0.842	5.57×10^{-6}	3.85×10^{-5}
${}^{124}_{50}Sn$	2.287	2.78×10^{-6}	2.33×10^{-5}	${}^{238}_{92}U$	1.145	2.94×10^{-6}	2.10×10^{-5}
${}^{128}_{52}Te$	0.867	1.57×10^{-5}	1.09×10^{-4}				

[Tretyak *et al.*, At. Data Nucl. Data Tables **80** (2002)]

Backup 2: Half-Lives Table

^{A}X	$T_{1/2}^{0\nu\beta\beta}$ [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}Ca	4.33×10^{27}	1.22×10^{34}	4.40×10^{19}	1.17×10^{25}
^{76}Ge	4.98×10^{26}	1.37×10^{32}	1.65×10^{21}	5.37×10^{25}
^{82}Se	1.40×10^{26}	7.08×10^{31}	9.20×10^{19}	5.02×10^{24}
^{96}Zr	1.90×10^{26}	2.47×10^{32}	2.30×10^{19}	3.16×10^{24}
^{100}Mo	6.24×10^{25}	1.73×10^{31}	7.10×10^{18}	2.16×10^{23}
^{110}Pd	1.84×10^{26}	1.86×10^{31}		
^{116}Cd	1.05×10^{26}	7.19×10^{31}	2.87×10^{19}	2.22×10^{24}
^{124}Sn	4.23×10^{26}	1.52×10^{32}		
^{128}Te	2.14×10^{27}	1.37×10^{32}	2.00×10^{24}	1.84×10^{28}
^{130}Te	1.17×10^{26}	4.34×10^{31}	6.90×10^{20}	3.01×10^{25}
^{134}Xe	3.12×10^{27}	1.88×10^{32}		
^{136}Xe	3.50×10^{26}	1.24×10^{32}	2.19×10^{21}	9.15×10^{25}
^{150}Nd	4.05×10^{25}	6.43×10^{31}	8.20×10^{18}	1.43×10^{24}
^{238}U			2.00×10^{21}	9.54×10^{25}

[Barabash, Nucl. Phys. A**935** (2015)]