Neutrinoless Double-Beta Decay with Emission of Single Electron

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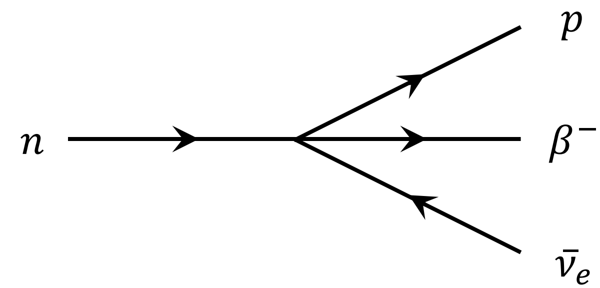
Double-Beta Decay

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



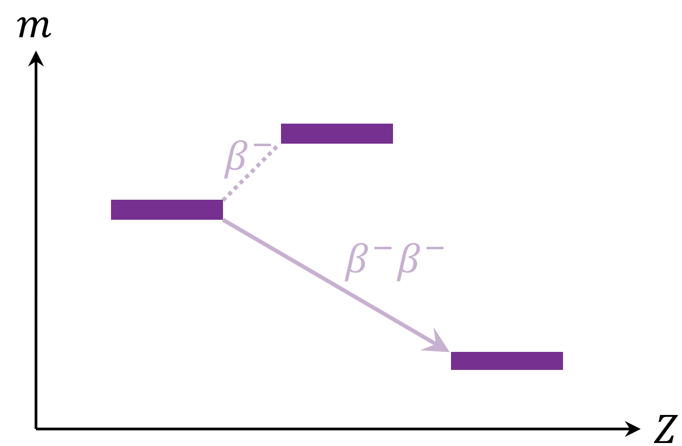
G_β: $G_{\mathrm{F}} \cos\theta_{\mathrm{C}}$

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

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

Double-beta decay ($2\nu\beta^-\beta^-$) is a rare 2nd-order process which can occur even if single-beta transition is forbidden or suppressed:

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



So far observed for 11 isotopes, with half-lives $\sim 10^{19}$—10^{21} y:

$^{48}\mathrm{Ca}$ $^{82}\mathrm{Se}$ $^{100}\mathrm{Mo}$ $^{128}\mathrm{Te}$ $^{136}\mathrm{Xe}$ $^{238}\mathrm{U}$

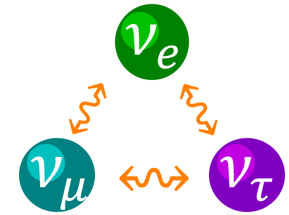
$^{76}\mathrm{Ge}$ $^{96}\mathrm{Zr}$ $^{116}\mathrm{Cd}$ $^{130}\mathrm{Te}$ $^{150}\mathrm{Nd}$

Neutrinoless Double-Beta Decay

Neutrino oscillations ⇒
ν are massive and mixed:

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

$\alpha = e, \mu, \tau$; $i = 1, 2, 3$



If massive neutrinos are Majorana fermions: $C\bar{\nu}_i^{\mathrm{T}}(x) = \nu_i(x)$

- Neutrinos ν_α ≡ antineutrinos $\bar{\nu}_\alpha$
- Total lepton number L is not strictly conserved
- Neutrinoless double-beta decay mode ($0\nu\beta^-\beta^-$) exists: $\Delta L = 2$

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

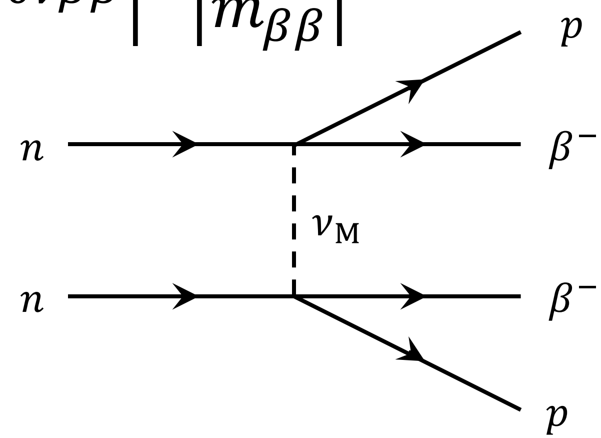
$0\nu\beta\beta$ decay rate:

$$\Gamma^{0\nu\beta\beta} = G^{0\nu\beta\beta}(Z,Q)\,\left|M^{0\nu\beta\beta}\right|^2 \left|m_{\beta\beta}\right|^2$$

$\Gamma^{0\nu\beta\beta}$: $\ln 2/T_{1/2}$; $G^{0\nu\beta\beta}(Z,Q)$: phase-space factor ; $M^{0\nu\beta\beta}$: nuclear matrix element

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

- Absolute scale of ν masses m_i
- Leptonic CP violation → baryon asymmetry
- KamLAND-Zen: $|m_{\beta\beta}| < 0.3$ eV

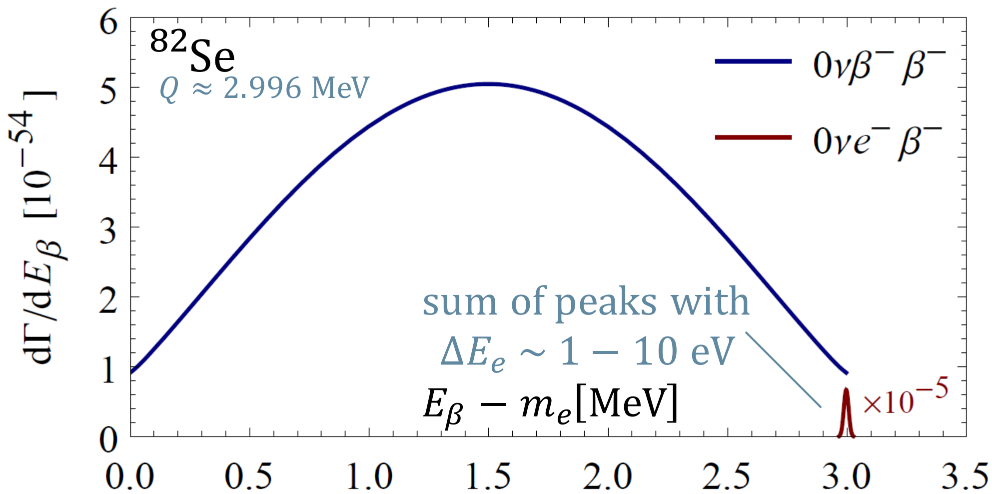


Single-Electron Mode of $0\nu\beta^-\beta^-$

$0\nu e^-\beta^-$: Nucleus is always surrounded by electron shells. What if one e^- remains bound and β^- particle carries away entire K.E. Q?

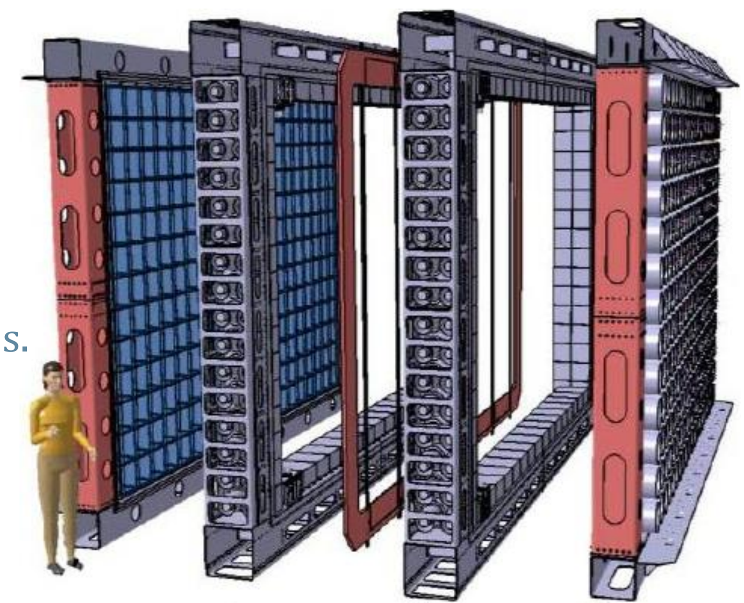
$$^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z+2}\mathrm{Y} + e^- + \beta^-$$

- e^-: Available $s_{1/2}$ and $p_{1/2}$ subshells of ${}^{A}_{Z+2}\mathrm{Y}^{2+}$ ion
- Peak at the endpoint of single-electron spectrum:



SuperNEMO:

- 20×5 kg source modules → thin foils of ^{82}Se or ^{150}Nd
- High-granularity tracking chamber → 9 ∥ of drift cells in $\vec{B}$ — particle ID & s. e. s.
- Segmented calorimeter walls → organic scintillator + PMT — FWHM$/E \approx 7\%/\sqrt{E}$ [MeV]



Relativistic Electron Wave Functions

Solutions to the stationary Dirac equation with Coulomb potential:

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

spinor spherical harmonics

$$\Omega_{\kappa\mu}(\hat{r}) = \sum_{\sigma=\pm 1/2} C^{j\mu}_{l,\mu-\sigma,1/2,\sigma}\, Y_{l,\mu-\sigma}(\hat{r})\,\chi^\sigma$$

$$\chi^{+1/2} = \binom{1}{0} \qquad \chi^{-1/2} = \binom{0}{1}$$

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

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

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

$\mathrm{s}_{1/2} \leftrightarrow \kappa = -1$

$\mathrm{p}_{1/2} \leftrightarrow \kappa = +1$

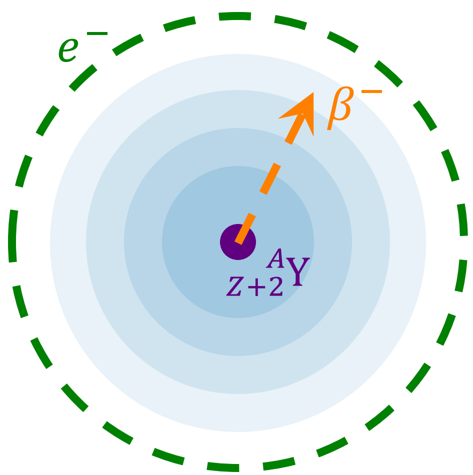
Screening effect → effective atomic number of daughter ion ${}^{A}_{Z+2}\mathrm{Y}^{2+}$:

- e^-: $Z_e \approx 2$
- β^-: $Z_\beta \approx Z + 2$

$$\mathrm{e}^{\mathrm{i}\vec{p}\cdot\vec{r}} = 4\pi \sum_{l=0}^{\infty} \sum_{m=-l}^{+l} \mathrm{i}^l\, j_l(pr)\, Y^*_{lm}(\hat{p})\, Y_{lm}(\hat{r})$$

Continuous spectrum → dominant term from partial-wave expansion:

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



$0\nu e^-\beta^-$ Decay Rate

$\boldsymbol{0\nu e^-\beta^-}$ decay rate:

$$\underbrace{E_\beta - m_e}_{\text{K. E. of } \beta^-} = Q + \underbrace{E_{n\kappa}}_{\text{B. E. of } e^-}$$

$$\Gamma^{0\nu e\beta} = \frac{G_\beta^4}{(2\pi)^3 4\pi R^2} \left|M^{0\nu\beta\beta}\right|^2 \left|m_{\beta\beta}\right|^2 \sum_n B(Z_e, E_e)\, F\left(Z_\beta, E_\beta\right) E_\beta\, p_\beta$$

vacant $s_{1/2}$ and $p_{1/2}$ subshells above valence shell of ${}^A_Z\mathrm{X}$
summed over numerically up to $n = 10^3$

Fermi functions:

$$B(Z, E_{n\kappa}) = f_{n,-1}^2(R) + g_{n,+1}^2(R)$$

$$F(Z, E) = f_{-1}^2(R, E) + g_{+1}^2(R, E)$$

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

$\boldsymbol{0\nu\beta^-\beta^-}$ decay rate:

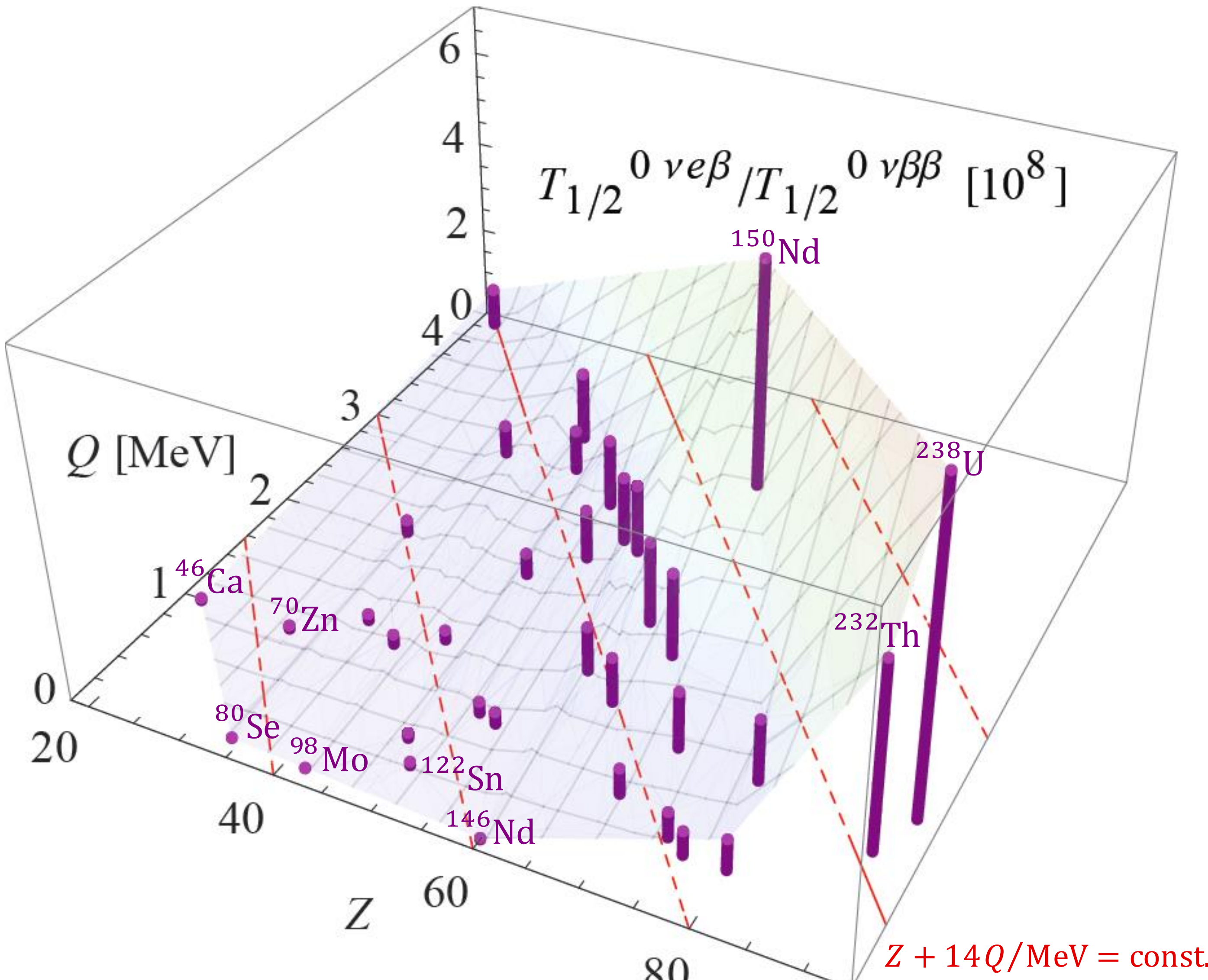
$$\Gamma^{0\nu\beta\beta} = \frac{G_\beta^4}{(2\pi)^5 R^2} \left|M^{0\nu\beta\beta}\right|^2 \left|m_{\beta\beta}\right|^2 \int_{m_e}^{m_e+Q} \mathrm{d}E_1\, F\left(Z_\beta, E_1\right) F\left(Z_\beta, E_2\right) E_1\, E_2\, p_1\, p_2$$

$p = \sqrt{E^2 - m_e^2}$

- Ratio $\Gamma^{0\nu e\beta} / \Gamma^{0\nu\beta\beta}$ does not depend on $M^{0\nu\beta\beta}$ and $m_{\beta\beta}$
  $\rightarrow$ purely kinematic problem!

Relative $0\nu e^-\beta^-$ Half-Lives $T_{1/2}^{0\nu e\beta}/T_{1/2}^{0\nu\beta\beta}$

${}^{A}_{Z}X$	Q [MeV]	$T_{1/2}^{0\nu e\beta}/T_{1/2}^{0\nu\beta\beta}$
${}^{46}_{20}Ca$	0.990	4.63×10^{6}
${}^{48}_{20}Ca$	4.272	8.20×10^{7}
${}^{70}_{30}Zn$	1.001	7.13×10^{6}
${}^{76}_{32}Ge$	2.039	2.64×10^{7}
${}^{80}_{34}Se$	0.134	7.31×10^{5}
${}^{82}_{34}Se$	2.996	6.16×10^{7}
${}^{86}_{36}Kr$	1.256	1.32×10^{7}
${}^{94}_{40}Zr$	1.144	2.03×10^{7}
${}^{96}_{40}Zr$	3.350	1.47×10^{8}
${}^{98}_{42}Mo$	0.112	9.23×10^{5}
${}^{100}_{42}Mo$	3.034	8.70×10^{7}
${}^{104}_{44}Ru$	1.300	2.00×10^{7}
${}^{110}_{46}Pd$	2.000	4.59×10^{7}
${}^{114}_{48}Cd$	0.537	1.04×10^{7}
${}^{116}_{48}Cd$	2.805	1.42×10^{8}
${}^{122}_{50}Sn$	0.366	7.29×10^{6}
${}^{124}_{50}Sn$	2.287	1.05×10^{8}
${}^{128}_{52}Te$	0.867	2.38×10^{7}
${}^{130}_{52}Te$	2.529	1.39×10^{8}
${}^{134}_{54}Xe$	0.830	2.48×10^{7}
${}^{136}_{54}Xe$	2.468	1.45×10^{8}
${}^{142}_{58}Ce$	1.417	9.35×10^{7}
${}^{146}_{60}Nd$	0.070	3.10×10^{6}
${}^{148}_{60}Nd$	1.929	1.73×10^{8}
${}^{150}_{60}Nd$	3.368	4.94×10^{8}
${}^{154}_{62}Sm$	1.251	9.45×10^{7}
${}^{160}_{64}Gd$	1.730	1.76×10^{8}
${}^{170}_{68}Er$	0.654	5.36×10^{7}
${}^{176}_{70}Yb$	1.087	1.19×10^{8}
${}^{186}_{74}W$	0.488	5.35×10^{7}
${}^{192}_{76}Os$	0.414	4.99×10^{7}
${}^{198}_{78}Pt$	1.047	1.29×10^{8}
${}^{204}_{80}Hg$	0.416	6.45×10^{7}
${}^{232}_{90}Th$	0.842	3.86×10^{8}
${}^{238}_{92}U$	1.145	6.67×10^{8}



***Q* values:**
[V. I. Tretyak and Y. G. Zdesenko, Atom. Data Nucl. Data Tabl. **80**, 83 (2002)]

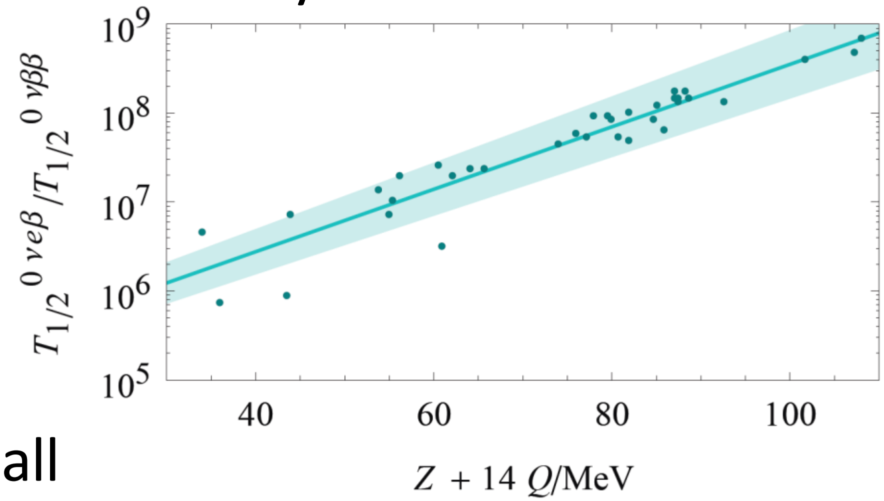
Conclusion & Outlook

Exponential fit with 1σ parametric uncertainty:

$$T_{1/2}^{0\nu e\beta}/T_{1/2}^{0\nu\beta\beta} \approx c e^{d(Z+14\,Q/\mathrm{MeV})}$$

$$c = 1.096^{+0.509}_{-0.347} \times 10^{5}$$

$$d = 8.078^{+0.499}_{-0.499} \times 10^{-2}$$



Conclusion:

- Effect of $0\nu e^-\beta^-$ on s.e.s. is small
- Primary source of overall suppression → screening effect of nuclear charge (substantial reduction of e^- wave function on R)

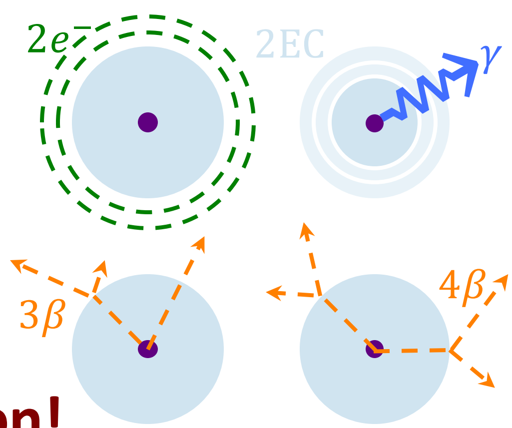
Outlook:

- Other interesting atomic modes of $\beta\beta$: $0\nu e^- e^-$, $0\nu\mathrm{ECEC}\gamma$, $0\nu3\beta$, $0\nu4\beta$, 2ν…
- Calorimetric exp. ECHo → m_β below eV

EC in ^{163}Ho

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2\, m_i^2} < 2.2\ \mathrm{eV}$$

effective ν mass



Thank you for your attention!