Nuclear-Structure Related Issues of Double Beta Decays

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Contents:

INTRO: Neutrino Properties from Experiments

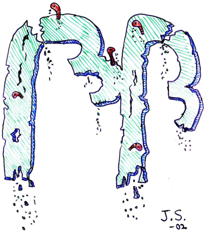
Neutrino Properties from Oscillation Experiments:

From solar, atmospheric, accelerator and reactor-neutrino data (SuperKamiokande, SNO, KamLAND, etc.):

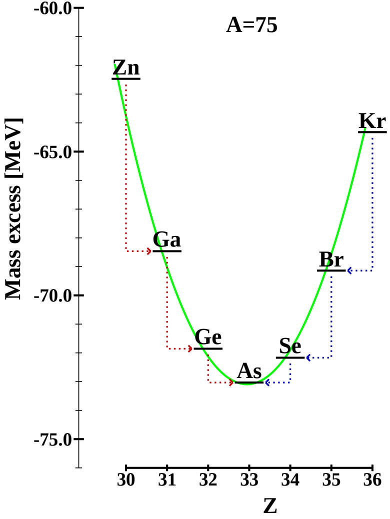
- Squared mass differences Δm^2 of neutrinos
- Matrix elements of the neutrino mixing matrix $\Leftrightarrow$ flavor eigenstates in terms of mass eigenstates: $\nu_{\rm e} \rightarrow \nu_i \rightarrow \nu_\mu \rightarrow \nu_j \rightarrow \nu_{\rm e} \rightarrow \nu_k \rightarrow \nu_\mu \cdots$

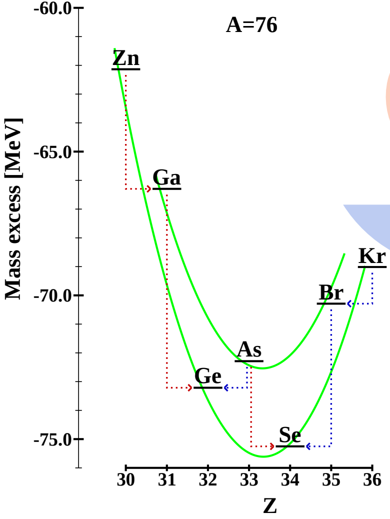
Complementary Experiments:

- Tritium beta decay (absolute neutrino mass), KATRIN
- **Double beta decay** (nature, absolute mass and hierarchy of neutrinos)



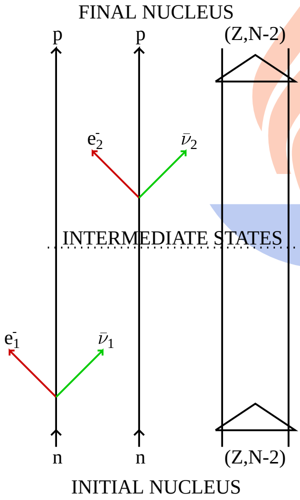
Double Beta Decay (Isobars $A = 76$)





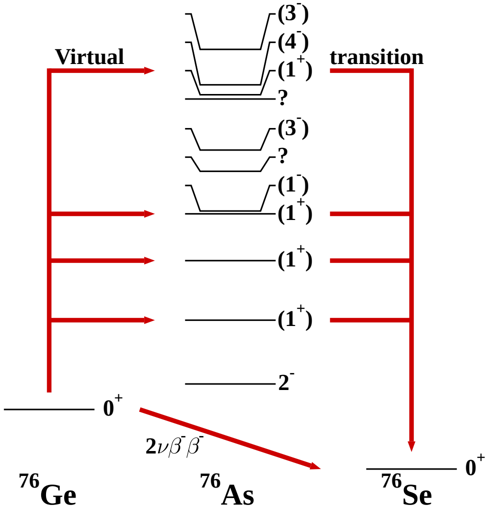
MODE I: Two-Neutrino Double Beta Decay

Nucleus	half-life (years)	experiments
^{48}Ca	$4.2 \cdot 10^{19}$	laboratory
^{76}Ge	$1.42 \cdot 10^{21}$	laboratory
^{82}Se	$9 \cdot 10^{19}$	laboratory, geochemical
^{96}Zr	$2.1 \cdot 10^{19}$	laboratory, geochemical
^{100}Mo	$8.0 \cdot 10^{18}$	laboratory
^{116}Cd	$3.3 \cdot 10^{19}$	laboratory
^{128}Te	$2.5 \cdot 10^{24}$	geochemical
^{130}Te	$9 \cdot 10^{20}$	geochemical
^{150}Nd	$7.0 \cdot 10^{18}$	laboratory
^{238}U	$2.0 \cdot 10^{21}$	radio-chemical



10^{20} years =
$10000000000 \times$ age of the UNIVERSE

INTRO: Two-Neutrino Double Beta Decay of ^{76}Ge

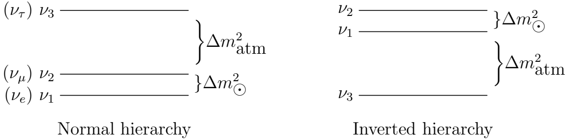


The decay goes through 1^+ virtual states

MODE II: Neutrinoless Double Beta Decay

$0\nu\beta\beta$ Decay is Able to:

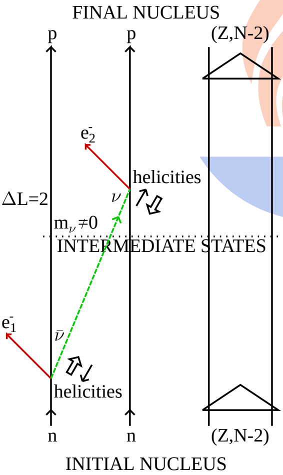
- Reveal if the neutrino is a Majorana particle
- Probe the neutrino effective mass $\langle m_\nu \rangle = \sum_{j=\text{light}} \lambda_j^{\text{CP}} |U_{ej}|^2 m_j$
- Probe the degenerate or inverted mass hierarchies (next-generation experiments!)
- Probe possibly the CP phases (nuclear matrix elements are critical!)



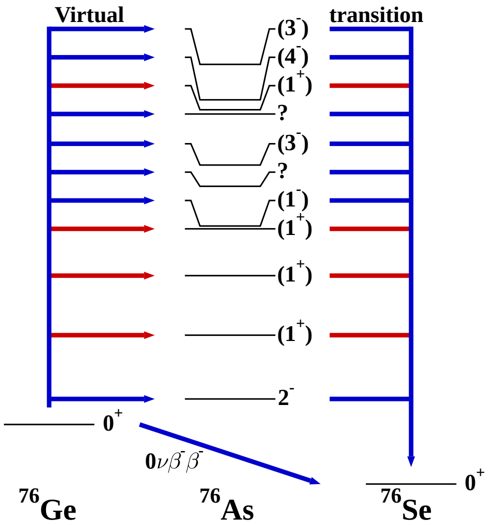
$$\Delta m^2_\odot = 7.67^{+0.16}_{-0.19} \times 10^{-5}\,\text{eV}^2$$
$$\Delta m^2_{\text{atm}} = 2.39^{+0.11}_{-0.08} \times 10^{-3}\,\text{eV}^2$$

[Global 3ν oscillation analysis (2008)]

MASS MODE:
$T_{1/2} \propto \langle m_\nu \rangle^2$



INTRO: Neutrinoless Double Beta Decay of ^{76}Ge



The decay goes through all J^π virtual states

Nuclear Matrix Elements and the $0\nu\beta\beta$ Decay

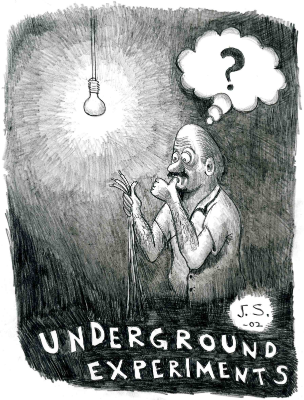
Decay rate:

$$\frac{\ln 2}{T_{1/2}} = g^{(0\nu)}(Q)[M^{(0\nu)}]^2\langle m_\nu\rangle^2$$

- $g^{(0\nu)}(Q) \propto Q^5$ is the phase-space factor
- $M^{(0\nu)}$ = NUCLEAR MATRIX ELEMENT
- Effective neutrino mass:

$$\langle m_\nu\rangle = \sum_{j=\text{light}} \lambda_j^{\text{CP}}|U_{ej}|^2 m_j$$

About Experiments



UNDERGROUND LABORATORIES protect from **COSMIC RAYS** and their secondary particles

Canfranc (Spain)
Kamioka (Japan)
Boulby (England)
Gran Sasso (Italy)
Pyhäsalmi (Finland)
Baksan (Ukraine)
Modane (France-Italy)
Sudbury (Canada)

Experiments Searching for $0\nu\beta\beta$ Decays:

Major Running Experiments:

- Heidelberg–Moscow (^{76}Ge) (ceased, claim of detection but result still **controversial**)
- NEMO3 (^{76}Ge ^{82}Se ^{96}Zr ^{100}Mo ^{116}Cd ...) running in Modane
- Cuoricino (^{128,130}Te) running in Gran Sasso

Future Experiments:

SUPERNEMO (^{82}Se ^{100}Mo...), GERDA (^{76}Ge), MAJORANA (^{76}Ge), CAMEOII,III (^{116}Cd), CUORE (^{128,130}Te), MOON (^{100}Mo), EXO (^{136}Xe), COBRA (^{70}Zn ^{106,114,116}Cd ^{128,130}Te), **ZORRO (^{96}Zr)**

These are in $100 - 1000$ kg scale and cost about 100000000 EURO/$ each!

New Challenges

Question:

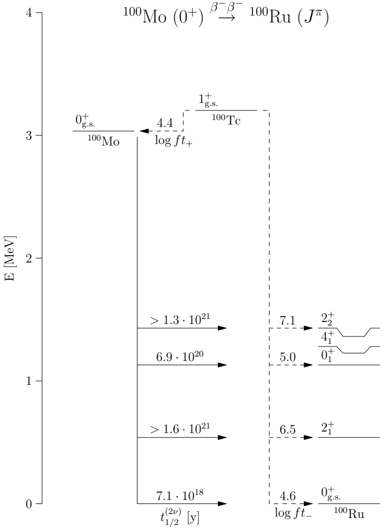
HOW CAN WE PROBE
THE VIRTUAL TRANSITIONS?

Complementary Experimental Probes $0\nu\beta\beta$ NMEs

Possible Experimental Probes:

- Beta decays (Need more data!) $\leftrightarrow$ Measurements of EC branches using the TITAN ion trap facility at TRIUMF
- Charge-exchange reactions [β^+-type (d,^{2}He) reactions at KVI, Groningen; β^--type (^{3}He,t) reactions at RCNP]
- Measurements of occupation numbers of active neutron orbitals $\leftrightarrow$ (d,p), (α,^{3}He) [add neutron] and (p,d), (^{3}He,α) [remove neutron]
- Measurements of occupation numbers of active proton orbitals $\leftrightarrow$ (^{3}He,d) [add proton] and (d,^{3}He) [remove proton]
- Ordinary muon capture (now experimentally feasible)

Nuclear Spectroscopy Associated to $\beta\beta$ Decays



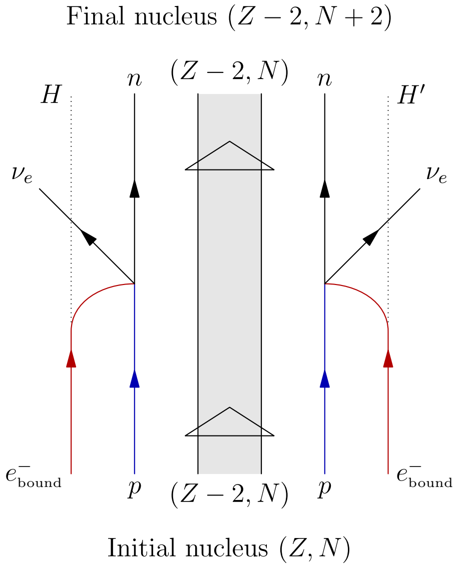
It is desirable to describe reliably

- Lateral feeding by single beta decays
- Branching of $2\nu\beta\beta$ decays
- Poperties of the final states (energies, quadrupole moments, one-phonon and two-phonon structures, intruder states)
- Electromagnetic transitions between the final states

Recent Work on Double Electron Capture

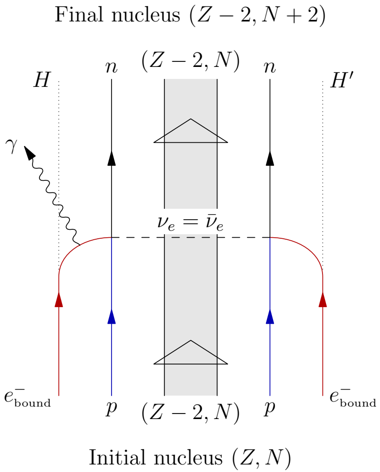
Resonant 0νECEC Decays

Two-Neutrino Double Electron Capture

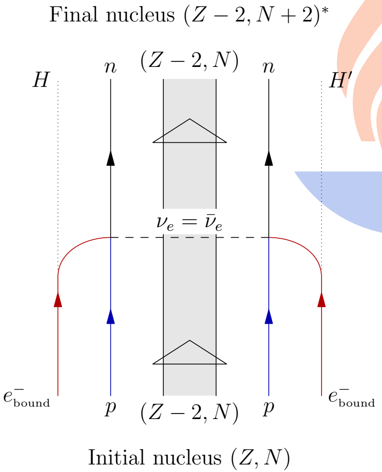


Neutrinoless Double Electron Capture

Radiative 0νECEC

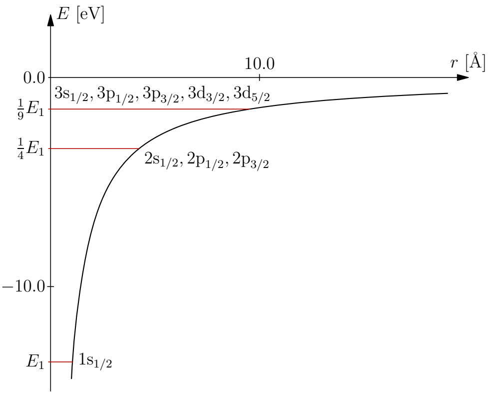


Resonant 0νECEC

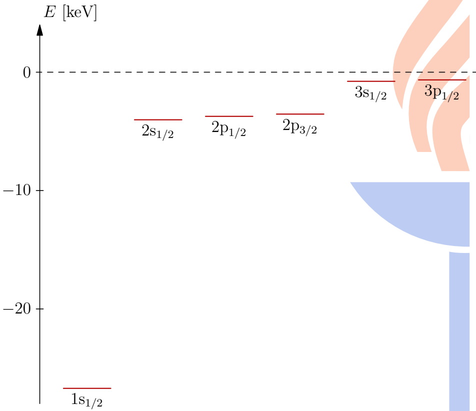


Single-Hole States in Atoms

Hydrogen atom



Cadmium atom



$$n = 1 \leftrightarrow \mathrm{K}\,, \quad n = 2 \leftrightarrow \mathrm{L}\,, \quad n = 3 \leftrightarrow \mathrm{M}\,, \; \ldots$$

Resonant 0νECEC Decay

Decay rate:

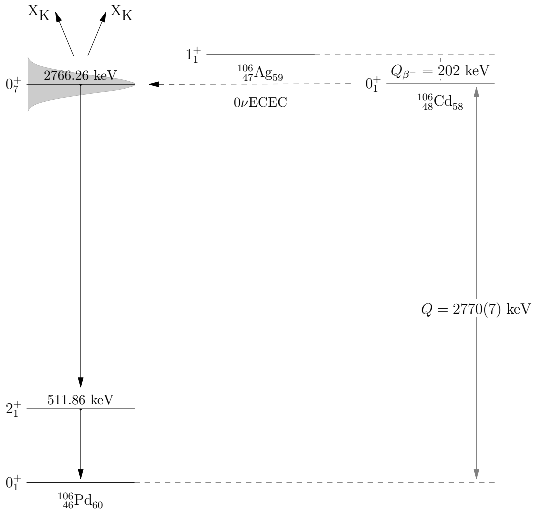
$$\frac{\ln 2}{T_{1/2}} = \frac{g^{\mathrm{ECEC}}[M^{\mathrm{ECEC}}]^2 \langle m_\nu \rangle^2}{(Q-E)^2 + \Gamma^2/4}\Gamma\,, \quad Q - E = \text{ degeneracy parameter}$$

- g^{ECEC} = phase-space factor
- $Q = M(Z,A) - M(Z-2,A)$ = difference between the initial and final atomic masses
- $E = E^* + E_H + E_{H'}$ = nuclear excitation energy + electron binding
- $\Gamma = \Gamma^* + \Gamma_H + \Gamma_{H'}$ = nuclear and atomic radiative widths
- M^{ECEC} = NUCLEAR MATRIX ELEMENT

Enhancement factors of 10^6 possible (J. Bernabeu, A. De Rujula, and C. Jarlskog, Nucl. Phys. B 223 (1983) 15 ; Z. Sujkowski and S. Wycech, Phys. Rev. C 70 (2004) 052501(R))

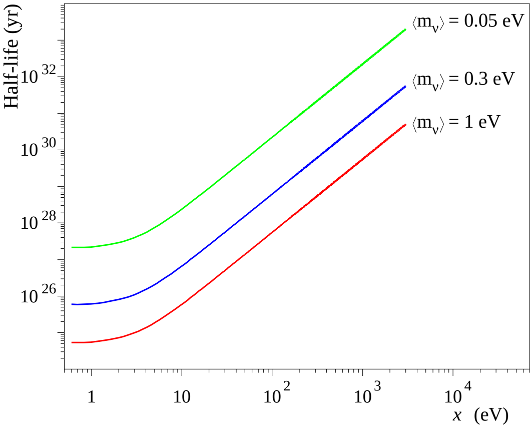
Candidates: $^{74}\mathrm{Se} \rightarrow {}^{74}\mathrm{Ge}(2^+)$, $^{78}\mathrm{Kr} \rightarrow {}^{78}\mathrm{Se}(2^+)$, $^{106}\mathrm{Cd} \rightarrow {}^{106}\mathrm{Pd}(0^+)$, $^{112}\mathrm{Sn} \rightarrow {}^{112}\mathrm{Cd}(0^+)$, $^{136}\mathrm{Ce} \rightarrow {}^{136}\mathrm{Ba}(0^+)$, . . .

Resonance 0νECEC Decay of ^{106}Cd



Half-life Estimate for ^{106}Cd

$$\Gamma = 6.1\,\mathrm{eV} \quad ; \quad M^{\mathrm{ECEC}} = 3.33 \quad \text{(unitless NME)}$$

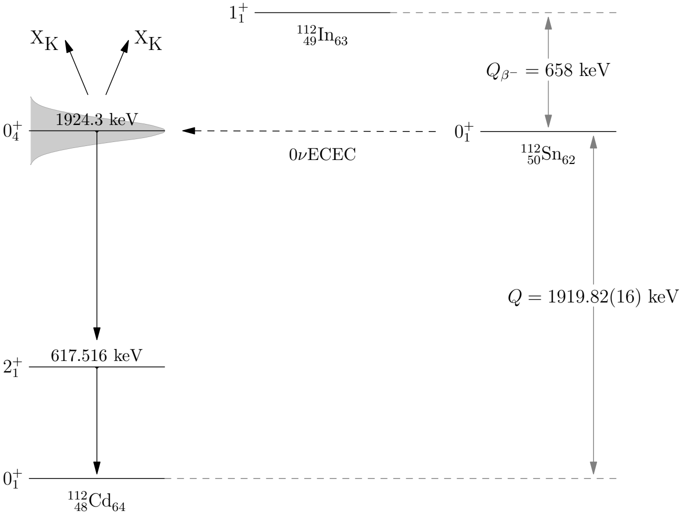


$$T_{1/2} = \ln 2 \frac{(x/\Gamma)^2 + 1/4}{g^{\mathrm{ECEC}}[M^{\mathrm{ECEC}}]^2 \langle m_\nu \rangle^2}\Gamma, \quad x = |Q - E|$$

Experimental Search for the Decay of ^{106}Cd

- Rita Bernabei *et al.*
- Use of $^{106}CdWO_4$ (cadmium-tungstate) crystal scintillators. Enriched ^{106}Cd up to 66%.
- The experiment (DAMA) is located at Gran Sasso National Laboratories near L'Aquila in Italy. First results after 779 hours of data taking.
- For the 0νECEC mode of decay: $T_{1/2} \geq 1.7 \times 10^{20}$ years

Resonance 0νECEC Decay of ^{112}Sn



Half-Life Estimate for ^{112}Sn

$$\Gamma = \text{few tens of eV} \quad ; \quad M^{\text{ECEC}} = 4.76 \quad \text{(unitless NME)}$$

Q value measured in JYFLTRAP (S Rahaman, V.-V. Elomaa, T. Eronen, J. Hakala, A. Jokinen, A. Kankainen, J. Rissanen, J. Suhonen, C. Weber, and J. Äystö, Phys. Rev. Lett. 103 (2009) 042501)

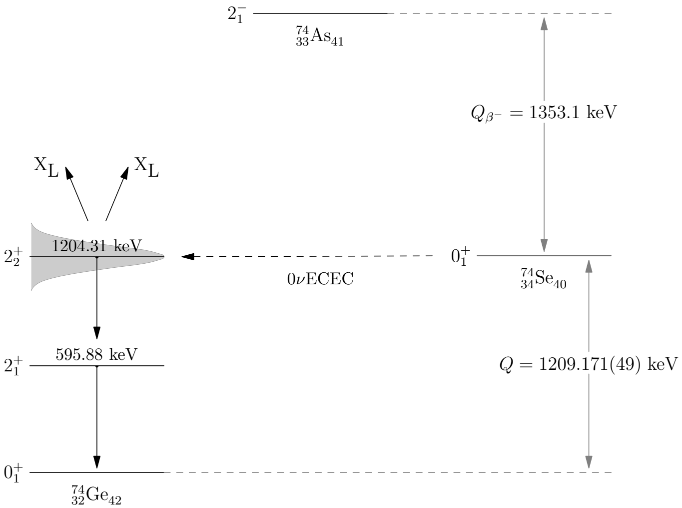
$Q - E$	$=$	$-4.5\,\text{keV}$	for	KK capture
	$=$	$18.2\,\text{keV}$	for	KL capture
	$=$	$40.9\,\text{keV}$	for	LL capture

Hence:

$$T_{1/2} > \frac{5.9 \times 10^{29}}{(\langle m_\nu \rangle [\text{eV}])^2}\ \text{years}$$

Conclusion: Decay rate much suppressed by the rather large degeneracy parameter $Q - E$

Resonance 0νECEC Decay of ^{74}Se



Half-Life Estimate for ^{74}Se

$$\Gamma = \text{few tens of eV} \quad ; \quad M_{0\nu}^{\text{ECEC}} < 0.0160 \quad \text{(unitless NME)}$$

Q value measured in JYFLTRAP (V.S. Kolhinen, V.-V. Elomaa, T. Eronen, J. Hakala, A. Jokinen, M. Kortelainen, J. Suhonen and J. Äystö, Phys. Lett. B 684 (2010) 17)

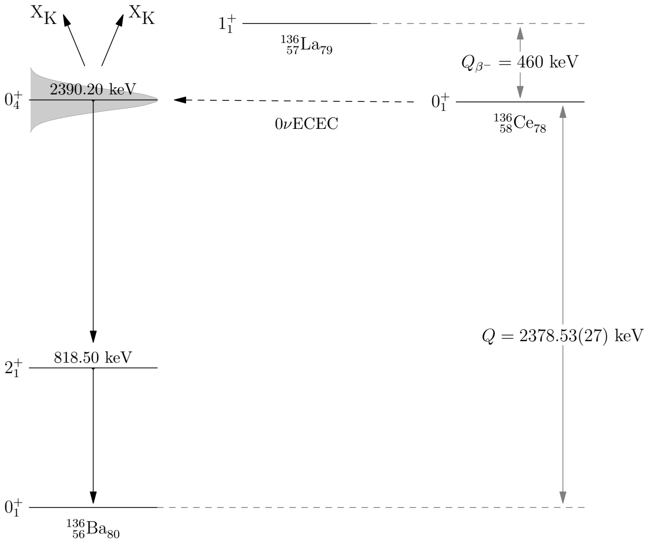
$$Q - E = 2.23\,\text{keV for LL capture (most favorable)}$$

Hence:

$$T_{1/2} \approx \frac{5 \times 10^{43}}{(\langle m_\nu \rangle [\text{eV}])^2}\ \text{years}$$

Conclusion: Decay rate much suppressed both by the rather large degeneracy parameter $Q - E$ and the very small NME for the 2_f^+ final state. The same occurs for the $2\nu\beta^-\beta^-$ decay (see M. Aunola and J. Suhonen, Nucl. Phys. A 602 (1996) 133)

Resonance 0νECEC Decay of ^{136}Ce



Half-Life Estimate for ^{136}Ce

$$\Gamma = 13.81\,\text{eV} \quad ; \quad M^{\text{ECEC}} = 0.250 \quad \text{(unitless NME)}$$

Q value measured in JYFLTRAP

$Q - E$	$=$	$-11.67\,\text{keV}$	for	KK capture
	$=$	$19.78\,\text{keV}$	for	KL capture
	$=$	$51.24\,\text{keV}$	for	LL capture

Hence:

$$T_{1/2} > \frac{2.26 \times 10^{33}}{(\langle m_\nu \rangle [\text{eV}])^2}\ \text{years}$$

Conclusion: Decay rate much suppressed by the rather large degeneracy parameter $Q - E$ and the rather small NME

Conclusions and Outlook

Conclusions:

- Calculatons of the NMEs of $0\nu\beta\beta$ decays are of vital importance for extracting information on the absolute neutrino mass
- The 0νECEC decay of ^{112}Sn is NOT OBSERVABLE due to badly fulfilled resonance condition
- The 0νECEC decays of ^{74}Se and ^{136}Ce are NOT OBSERVABLE due to badly fulfilled resonance condition and tiny NME

Outlook:

- Other resonant 0νECEC decays, like the one of ^{106}Cd, should be studied for their Q values using the atom trap techniques
- Data on spectroscopic properties of nuclei should be extended to better test the nuclear-structure models used in double-beta calculations