Nuclear Matrix Elements for Rare Decays

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- The Rare Beta Decay of ^{115}In

Topic I

Resonant 0νECEC Decays

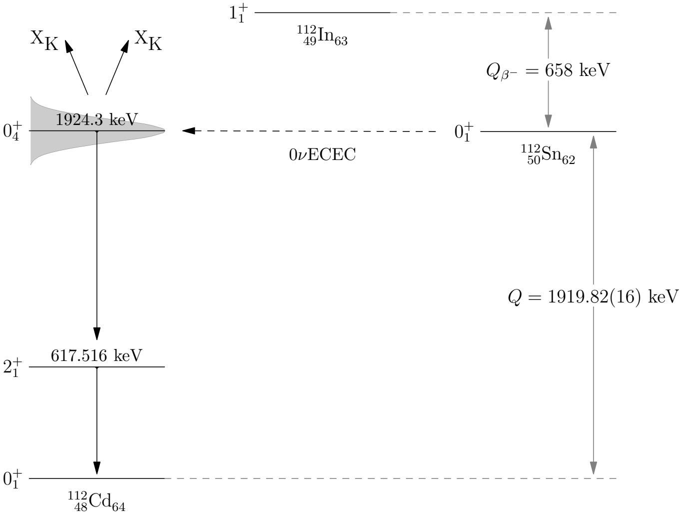
The 0νECEC decay rate can be enhanced by the resonance condition:

$$\frac{1}{T_{1/2}} = \frac{(\Delta M)^2}{(Q-E)^2 + \Gamma^2/4}\Gamma \,, \quad Q - E = \text{ degeneracy parameter}$$

- ΔM = atom-mixing parameter containing the nuclear matrix element
- $Q = M(Z,A) - M(Z-2,A)$ = 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

Candidates: $^{74}\mathrm{Se} \to {}^{74}\mathrm{Ge}(2^+)$, $^{78}\mathrm{Kr} \to {}^{78}\mathrm{Se}(2^+)$, $^{112}\mathrm{Sn} \to {}^{112}\mathrm{Cd}(0^+)$, ...

Resonance decay of ^{112}Sn



The Atom-Mixing Parameter

$$\Delta M = G_{0\nu}^{\mathrm{ECEC}} M_{0\nu}^{\mathrm{ECEC}} \langle m_\nu \rangle \ ,$$

with phase-space factor

$$G_{0\nu}^{\mathrm{ECEC}} = \left(\frac{G_{\mathrm{F}} \cos\theta_{\mathrm{C}}}{\sqrt{2}} \right) \frac{g_{\mathrm{A}}^2}{2\pi} \frac{(Z\alpha m_{\mathrm{e}})^3}{\pi R_A} \ , \quad R_A = 1.2 A^{1/3} \ ,$$

and NUCLEAR MATRIX ELEMENT

$$\mathbf{M}_{0\nu}^{\mathrm{ECEC}} = \sum_a (J_{\mathrm{f}}^+ || \sum_{m,n} \tau_m^+ \tau_n^+ h(r_{mn}, E_a) f_J(\boldsymbol{\sigma}_m, \boldsymbol{\sigma}_n) || 0_{\mathrm{i}}^+) \ , \quad r_{mn} = |\mathbf{r}_m - \mathbf{r}_n| \ .$$

Here $h(r_{mn}, E_a)$ is the neutrino potential containing, e.g., short-range correlations, and

$$f_0(\boldsymbol{\sigma}_m, \boldsymbol{\sigma}_n) = \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n \quad (J_{\mathrm{f}}^+ = 0_{\mathrm{f}}^+) \ ,$$

$$f_2(\boldsymbol{\sigma}_m, \boldsymbol{\sigma}_n) = [\boldsymbol{\sigma}_m \boldsymbol{\sigma}_n]_2 \quad (J_{\mathrm{f}}^+ = 2_{\mathrm{f}}^+) \ ,$$

$$\langle m_\nu \rangle = \sum_{j=\mathrm{light}} \lambda_j^{\mathrm{CP}} |U_{\mathrm{e}j}|^2 m_j \ .$$

Resonance 0νECEC decay of ^{112}Sn

Γ = few tens of eV ; $M_{0\nu}^{\rm ECEC} = 4.76$ (unitless NME)

Q value measured in JYFLTRAP (Phys. Rev. Lett. 103 (2009) 042501)

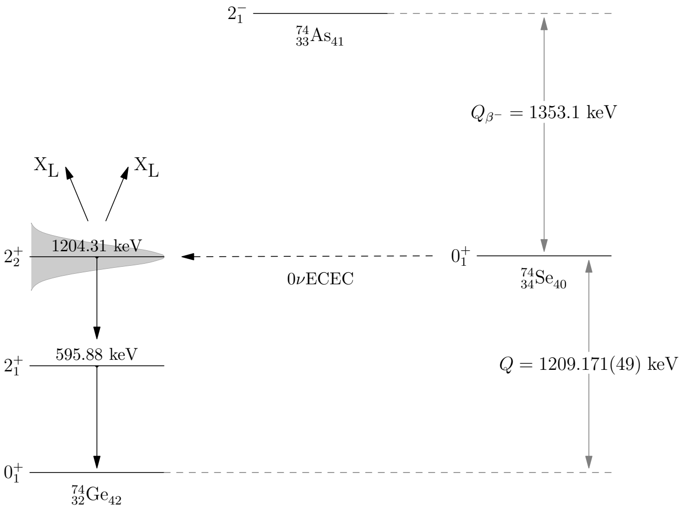
$Q - E$	$=$	$-4.5\,\mathrm{keV}$	for	KK capture
	$=$	$18.2\,\mathrm{keV}$	for	KL capture
	$=$	$40.9\,\mathrm{keV}$	for	LL capture

Hence:

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

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

Resonance decay of ^{74}Se



Resonance 0νECEC decay of ^{74}Se

Γ = few tens of eV ; $M_{0\nu}^{\rm ECEC} = 0.0160$ (unitless NME)

Q value measured in JYFLTRAP (to be submitted)

$Q - E = 2.23\,$keV for LL capture (most favourable)

Hence:

$$T_{1/2} \approx \frac{9.45 \times 10^{34}}{(\langle m_\nu \rangle [\mathrm{eV}])^2}\ \text{years}$$

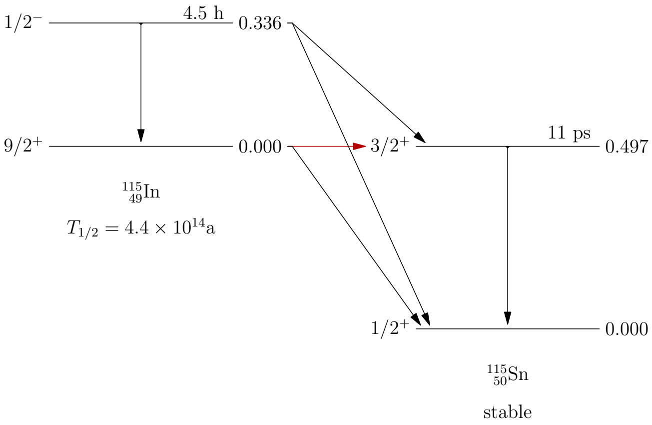
Conclusion: Decay rate much suppressed both by the rather large degeneracy parameter $Q - E$ and the very small NME for the 2^+_f final state. The same occurs for the $2\nu\beta^-\beta^-$ decay (see M. Aunola and J. Suhonen, Nucl. Phys. A 602 (1996) 133)

Topic II

^{115}In: Beta decay with an ultra-low Q value

^{115}In: Beta decay with an ultra-low Q value

First discovered by Cattadori et al. (Nucl. Phys. A 748 (2005) 333)



Suggested as a possible independent experiment to look for the neutrino mass

Experimental results

LNGS (C.M. Cattadori et al.)	first observation
	$b = 1.18(31) \times 10^{-6}$
	$T_{1/2}^{\text{partial}} = 3.73(98) \times 10^{20}$ a
HADES*	$b = 1.07(17) \times 10^{-6}$
	$T_{1/2}^{\text{partial}} = 4.1(6) \times 10^{20}$ a
JYFLTRAP*	$Q_{\beta^-} = 0.35(17)$ keV

* J.S.E. Wieslander, J. Suhonen, T. Eronen, M. Hult, V.-V. Elomaa, A. Jokinen, G. Marissens, M. Misiaszek, M.T. Mustonen, S. Rahaman, C. Weber and J. Äystö, Phys. Rev. Lett. 103 (2009) in press.

Lowest Q value recorded so far!

Previous record: ^{187}Re $Q_{\beta^-} = 2.469(4)$ keV [1]

[1] M.S. Basunia, Nucl. Data Sheets 110 (2009) 999.

Theory

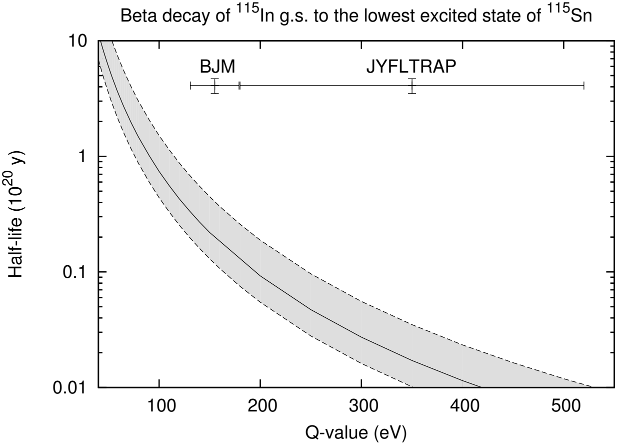
- 2nd-forbidden unique $^{115}\mathrm{In}(9/2^+) \to {}^{115}\mathrm{Sn}(3/2^+)$ decay
- dependent on only one nuclear matrix element (NME) M

$$T_{1/2} = \frac{1}{M^2 f_K(w_0, Z_f, R)}$$

- wave functions from the proton-neutron microscopic quasiparticle-phonon model (pnMQPM)
- pnMQPM was previously successfully applied to the 4th-forbidden non-unique $^{115}\mathrm{In}(9/2^+) \to {}^{115}\mathrm{Sn}(1/2^+)$ g.s.-to-g.s. decay ($\log ft$, half-life, electron spectrum) [2]

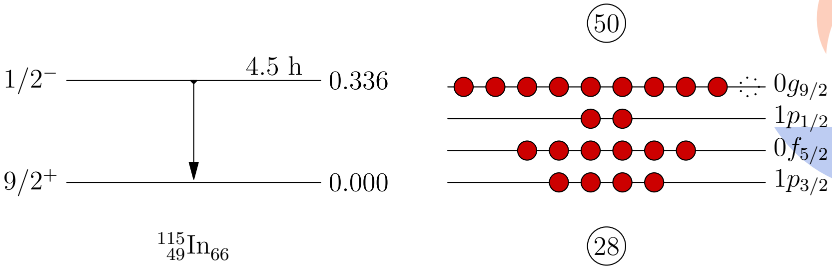
[2] M.T. Mustonen and J. Suhonen, Phys. Lett. B 657 (2007) 38.

Experiments meet theory

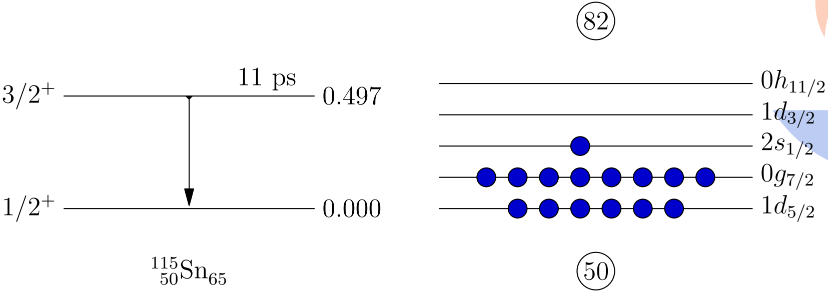


BJM = B.J. Mount, M. Redshaw and E.G. Myers, Phys. Rev. Lett. 103 (2009) in print

Nuclear wave functions: Naïve picture for protons (In)



Nuclear wave functions: Naïve picture for neutrons (Sn)



Possible sources of the discrepancy

Nuclear wave functions?

- MQPM and pnMQPM take also into account the 3-qp degrees of freedom
  $\Rightarrow$ Relevant states still dominantly 1-qp states
- To explain the discrepancy, the NME should be wrong by a factor of 5 or more!
- Maybe the problem lies in the *lepton* wave functions...

Atomic effects for ultra-low Q values

- electron screening (not estimated for forbidden decays)
- atomic overlap (previous approximations break down)
- exchange effects (contradictory results for low Q values)
- final-state interactions (estimates only for tritium beta decay)

Conclusions and Outlook

Conclusions:

- The 0νECEC decay of ^{112}Sn is NOT OBSERVABLE due to badly fulfilled resonance condition
- The 0νECEC decay of ^{74}Se is NOT OBSERVABLE due to badly fulfilled resonance condition and tiny NME
- ^{115}In decays by an ultra-low Q value $\longrightarrow$ ATOMIC effects important

Outlook:

- Other resonant 0νECEC decays should be studied for their Q values using the atom trap techniques
- Much work needed to chart the magnitudes of the atomic effects in beta decays with ultra-low Q values. Only then the hunt for the elusive neutrino mass in these decays is possible.