Neutrinoless Double EC and Rare Beta Decays as Tools to Search for the Neutrino Mass

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Contents:

INTRO: Neutrino Properties from Experiments

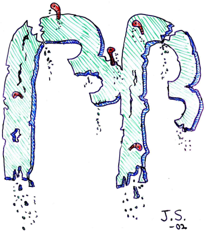
Neutrino Properties from Oscillation Experiments:

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: $\nu_e \rightarrow \nu_i \rightarrow \nu_\mu \rightarrow \nu_j \rightarrow \nu_e \rightarrow \nu_k \rightarrow \nu_\mu \cdots$

Complementary Experiments:

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

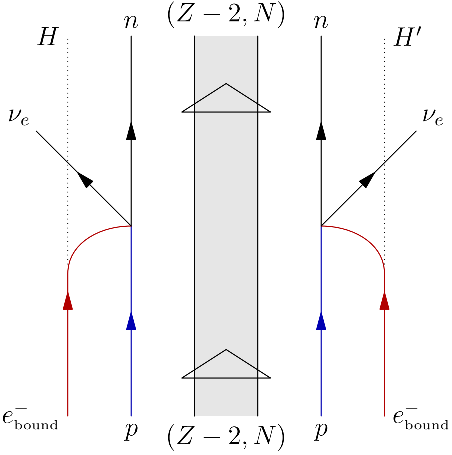


Topic I

Resonant 0νECEC Decays

Two-Neutrino Double Electron Capture

Final nucleus $(Z-2, N+2)$

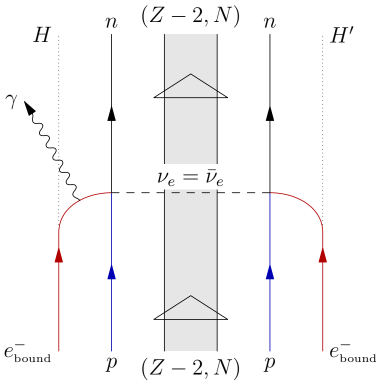


Initial nucleus (Z, N)

Neutrinoless Double Electron Capture

Radiative 0νECEC

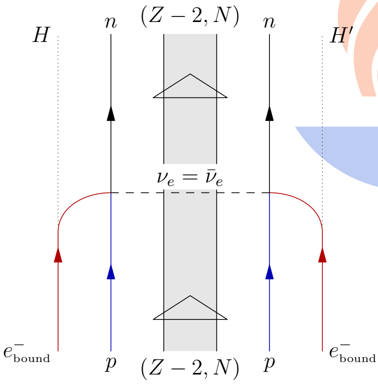
Final nucleus $(Z-2, N+2)$



Initial nucleus (Z, N)

Resonant 0νECEC

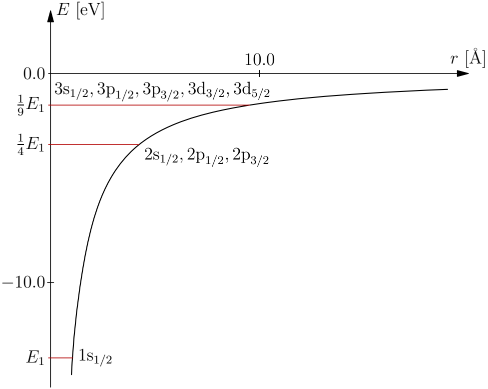
Final nucleus $(Z-2, N+2)^*$



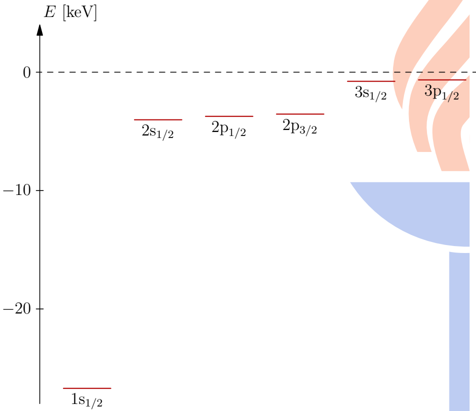
Initial nucleus (Z, N)

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:

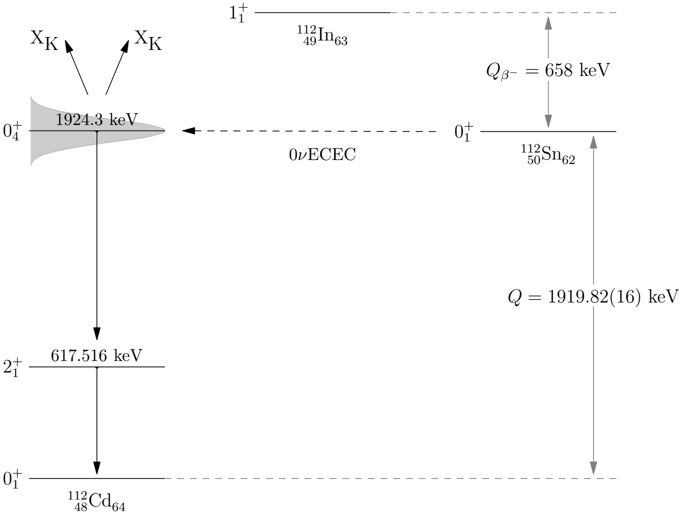
$$\frac{\ln 2}{T_{1/2}} = \frac{g^{\mathrm{ECEC}}[M^{\mathrm{ECEC}}]^2 \langle m_\nu \rangle^2}{(Q-E)^2 + \Gamma^2/4}\Gamma\,, \qquad Q-E = \text{ degeneracy parameter}$$

- 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}Se $\rightarrow$ ^{74}Ge(2^+), ^{78}Kr $\rightarrow$ ^{78}Se(2^+), ^{112}Sn $\rightarrow$ ^{112}Cd(0^+), ...

Resonance 0νECEC Decay of ^{112}Sn



Half-Life Estimate for ^{112}Sn

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

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)

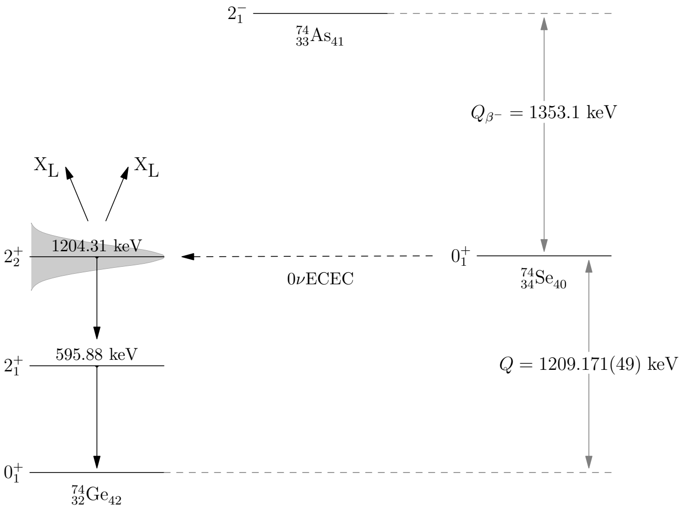
$Q - E$	$=$	$-4.5\,$keV	for	KK capture
	$=$	$18.2\,$keV	for	KL capture
	$=$	$40.9\,$keV	for	LL capture

Hence:

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

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

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

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:

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

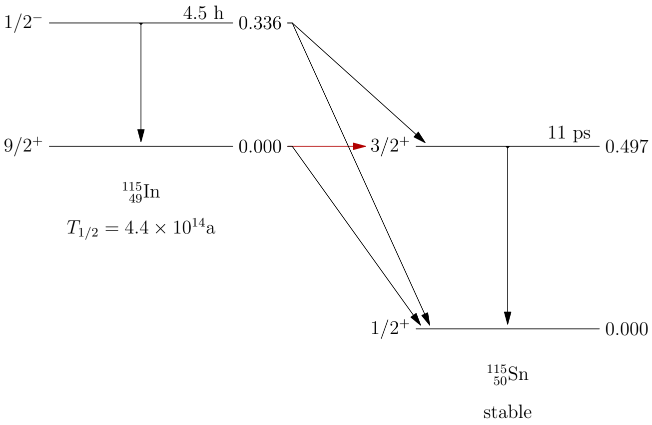
Conclusion: Decay rate much suppressed both by the rather large degeneracy parameter $Q - E$ and the very small NME for the 2_f^+ final state. The same occurs for the $2\nu\beta^-\beta^-$ decay (see M. Aunola and J. Suhonen, Nucl. Phys. A 602 (1996) 133)

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) 122501.

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

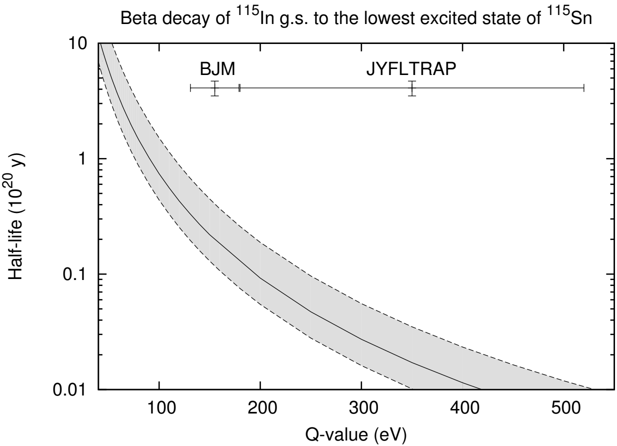
- 2nd-forbidden unique $^{115}\mathrm{In}(9/2^+) \rightarrow {}^{115}\mathrm{Sn}(3/2^+)$ decay
- dependent on only one nuclear matrix element (NME) M

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

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

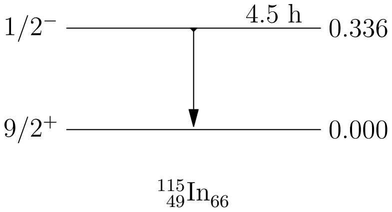
[2] M.T. Mustonen and J. Suhonen, Phys. Lett. B 657 (2007) 38.

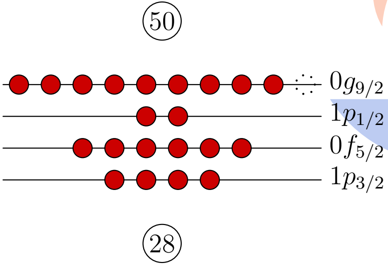
Experiments Meet Theory



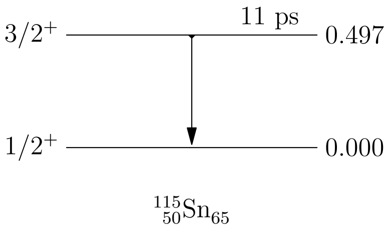
BJM = B.J. Mount, M. Redshaw and E.G. Myers, Phys. Rev. Lett. 103 (2009) 122502

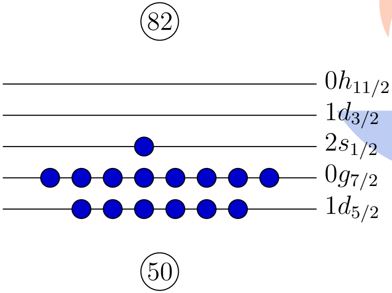
Nuclear Wave Functions: Naïve Picture for Protons (In)





Nuclear Wave Functions: Naïve Picture for Neutrons (Sn)





Possible Sources of 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.

Donald Henry Rumsfeld about atomic effects in CBS-NEWS:

Direct quotation:

'... there are known knowns. These are things we know that we know. There are known unknowns, that is to say, there are things that we now know we don't know. But there are also unknown unknowns, there are things we do not know we don't know.'