

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

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Fifth International BEYOND 2010 Conference, Cape Town, South Africa, 1-6 February, 2010



## Contents:

- Intro
- Resonant  $0\nu$ ECEC Decays
- The Rare Beta Decay of  $^{115}\text{In}$

# INTRO: Neutrino Properties from Experiments

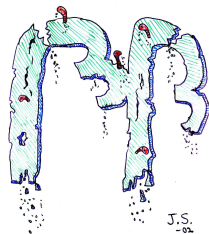
## Neutrino Properties from Oscillation Experiments:

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

- Squared mass differences  $\Delta m^2$  of neutrinos
- Matrix elements of the neutrino mixing matrix  $\Leftrightarrow$  flavor eigenstates in terms of mass eigenstates:  $\nu_e \rightarrow \nu_i \rightarrow \nu_\mu \rightarrow \nu_j \rightarrow \nu_e \rightarrow \nu_k \rightarrow \nu_\mu \dots$

## Complementary Experiments:

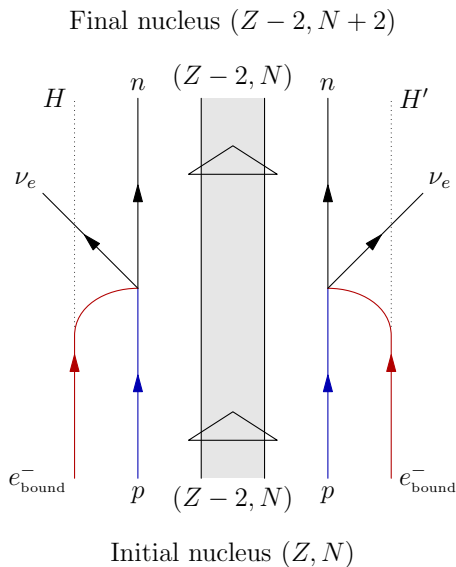
- Tritium beta decay (absolute neutrino mass), KATRIN
- **Double beta decay** (nature, absolute mass and hierarchy of neutrinos)



## Topic I

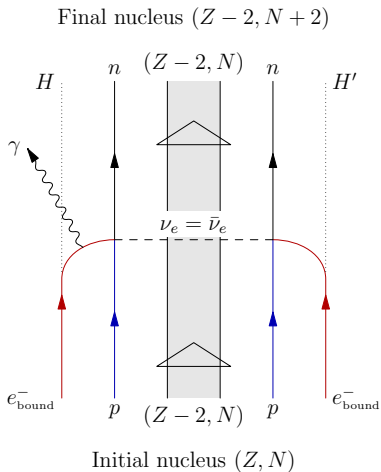
# Resonant $0\nu$ ECEC Decays

# Two-Neutrino Double Electron Capture

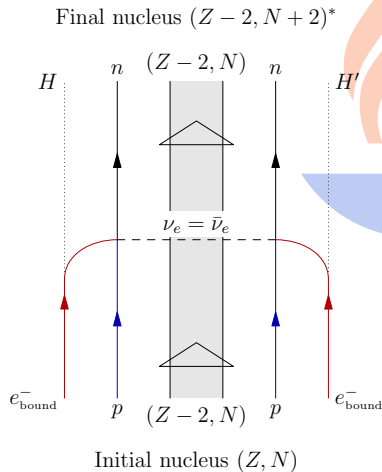


# Neutrinoless Double Electron Capture

## Radiative $0\nu$ ECEC

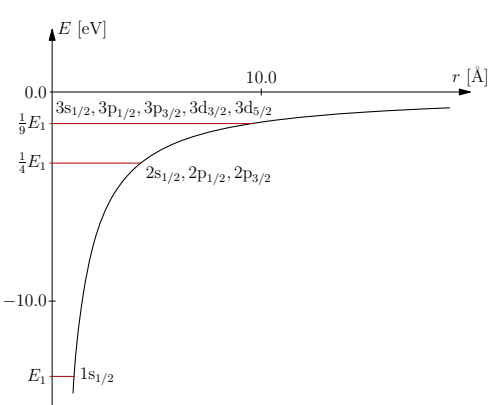


## Resonant $0\nu$ ECEC



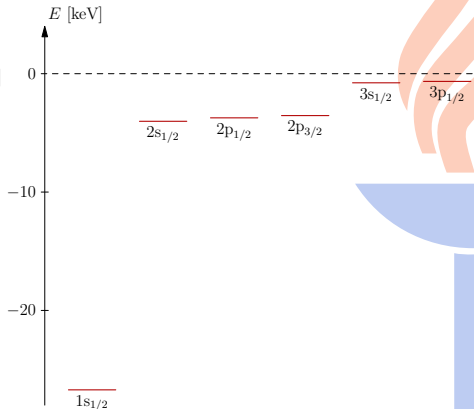
# Single-Hole States in Atoms

## Hydrogen atom



$$n = 1 \leftrightarrow K, \quad n = 2 \leftrightarrow L, \quad n = 3 \leftrightarrow M, \dots$$

## Cadmium atom



# Resonant $0\nu$ ECEC Decay

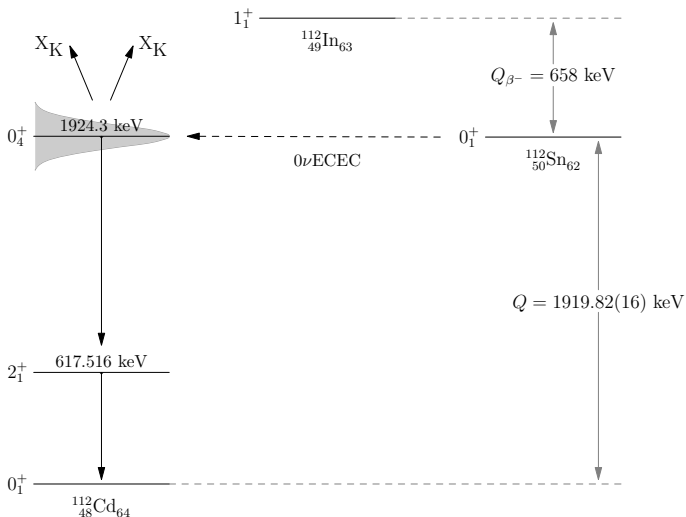
Decay rate:

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

- $g^{\text{ECEC}}$  = 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
- $M^{\text{ECEC}}$  = 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:  ${}^{74}\text{Se} \rightarrow {}^{74}\text{Ge}(2^+)$ ,  ${}^{78}\text{Kr} \rightarrow {}^{78}\text{Se}(2^+)$ ,  ${}^{112}\text{Sn} \rightarrow {}^{112}\text{Cd}(0^+)$ , ...

Resonance  $0\nu$ ECEC Decay of  $^{112}\text{Sn}$ 

# Half-Life Estimate for $^{112}\text{Sn}$

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

$Q$  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)

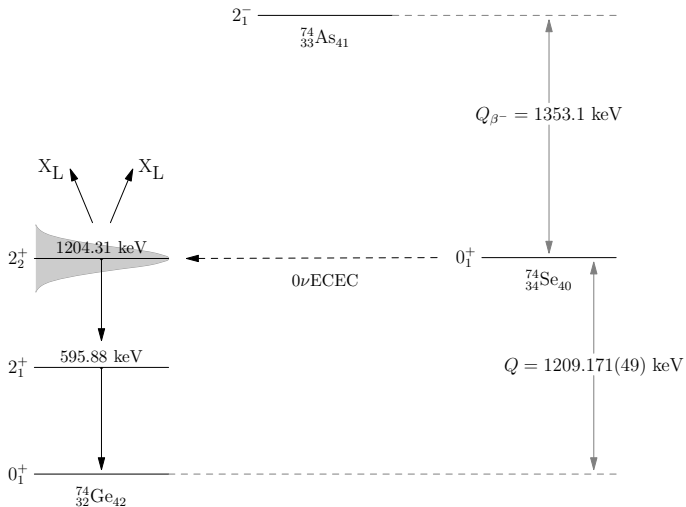
$Q - E$	=	-4.5 keV	for	KK capture
	=	18.2 keV	for	KL capture
	=	40.9 keV	for	LL capture

Hence:

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

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

# Resonance $0\nu$ ECEC Decay of $^{74}\text{Se}$



# Half-Life Estimate for $^{74}\text{Se}$

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

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

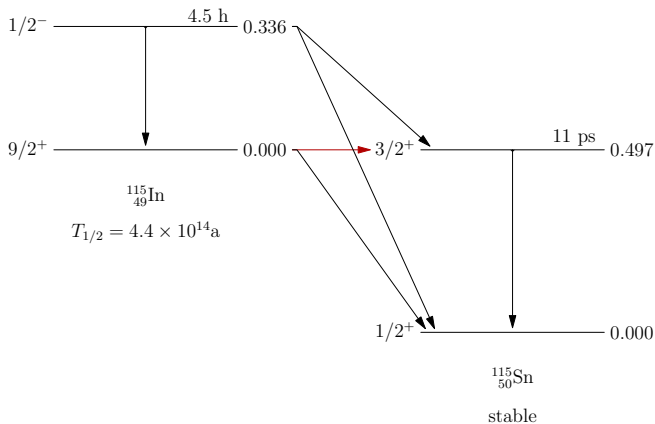
**Conclusion:** Decay rate much suppressed both by the rather large degeneracy parameter  $Q - E$  and the very small NME for the  $2_f^+$  final state. The same occurs for the  $2\nu\beta^-\beta^-$  decay (see M. Aunola and J. Suhonen, Nucl. Phys. A 602 (1996) 133)

## Topic II

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

# $^{115}\text{In}$ : 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 $b = 1.18(31) \times 10^{-6}$ $T_{1/2}^{\text{partial}} = 3.73(98) \times 10^{20} \text{ a}$
HADES*	$b = 1.07(17) \times 10^{-6}$ $T_{1/2}^{\text{partial}} = 4.1(6) \times 10^{20} \text{ a}$
JYFLTRAP*	$Q_{\beta^-} = 0.35(17) \text{ keV}$

\* 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:  $^{187}\text{Re } Q_{\beta^-} = 2.469(4) \text{ keV}^1$

<sup>1</sup>M.S. Basunia, Nucl. Data Sheets 110 (2009) 999.

# Theory

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

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

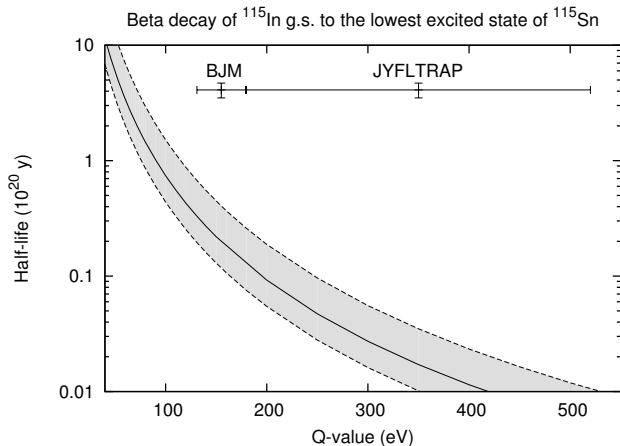
- wave functions from the proton-neutron microscopic quasiparticle-phonon model (pnMQPM)
- pnMQPM was previously successfully applied to the 4th-forbidden non-unique  $^{115}\text{In}(9/2^+) \rightarrow ^{115}\text{Sn}(1/2^+)$  g.s.-to-g.s. decay ( $\log ft$ , half-life, electron spectrum)<sup>2</sup>

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<sup>2</sup>M.T. Mustonen and J. Suhonen, Phys. Lett. B 657 (2007) 38.

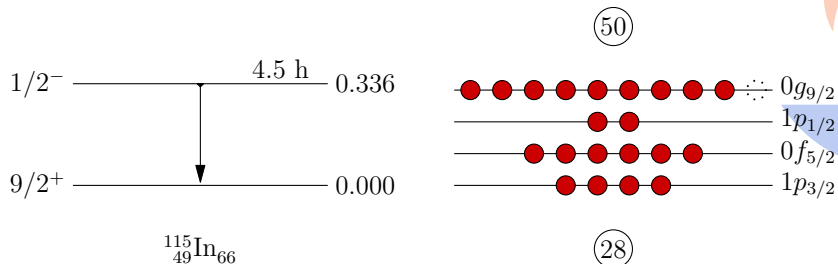


# Experiments Meet Theory

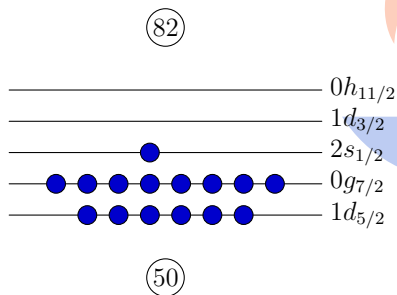
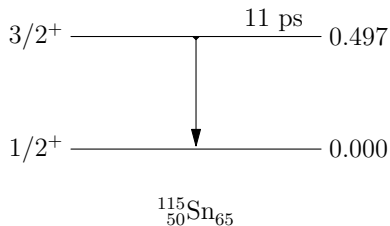


BJM = B.J. Mount, M. Redshaw and E.G. Myers, Phys. Rev. Lett. 103 (2009) 122502

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

## Outlook:

- Other resonant  $0\nu$ ECEC 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.'