Relic Antineutrino Capture

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Relic neutrinos

- As well as the 2.7 K microwave background radiation, the universe is filled with a sea of relic ν's that decoupled from the rest of the universe within the first few seconds after the Big Bang.
- These relic ν's may have played a crucial role in nucleosynthesis, structure formation and the evolution of the universe as a whole.

→ A non-zero ν mass can dramatically change the properties of the relic ν sea and its role in the evolution of the universe.

→ The current cosmological upper limit on the average ν mass is ~0.2 eV (from Planck 2013).

Most copious relic particles

Relic photons(~3x10^{87})

- They are bosons.
- They were decoupled when
  - the Universe was 4x10^5 y old
  - the average energy was 0.25eV
  - the temperature was 3000 ˚K
- As the Universe expanded their temperature dropped to 2.72 ˚K.
- It is higher because of reheating

$$e^+ + e^- \rightleftharpoons \gamma + \gamma$$

- Today average energy

  → 6.3x10^{-4} eV

Relic neutrinos (~10^{87})

- They are fermions.
- They were decoupled when
  - the Universe was 1s old
  - the average energy was 1MeV
  - the temperature was 10^{10} ˚K
- As the Universe expanded their temperature dropped to 1.95 ˚K
- No reheating after 1s.
- Today average energy

  → 5.0x10^{-4} eV

✓ Nobody has yet seen relic neutrinos.

Relic neutrinos

- The low energy nuclear β or EC decays are excellent tools for testing non-zero ν masses.
- Among all β unstable nuclides, $^{3}H(Q_{\beta-}=18.5906\ \mathit{32}\ \mathrm{keV})$, $^{187}Re(Q_{\beta-}=2.4670\ \mathit{20}\ \mathrm{keV})$ & $^{163}Ho(Q_{EC}=2833(30stat)(15sys)\ \mathrm{eV})$ are attractive for 'non-zero ν mass' experiment due to their low Q-values.
- Recently the interest in ^{163}Ho has been renewed because of a possible relic $\bar{\nu}$ capture experiment.

Relic neutrino experiments

- Lusignoli & Vignati
  ‘Relic $\bar{\nu}$ capture on ^{163}Ho decaying nuclei’
  [PLB 697, 11 (2011) & PLB 701, 673 (2011) (E)]

- Li & Xing, ‘A possible detection of the cosmic $\bar{\nu}$ background in the presence of flavor effects’
  [PLB 698, 430 (2011)]
- Galeazzi et al., ‘The electron capture decay of ^{163}Ho to measure the electron neutrino mass with sub-eV accuracy’
  [arXiv:1202.4763v3]
- Blaum et al., ‘The electron capture ^{163}Ho experiment ECHo’
  [arXiv:1306.2655v1]
- S. Eliseev et al.,‘Direct measurement of the mass difference of ^{163}Ho and ^{163}Dy solves the Q-value puzzle for the neutrino mass determination’, PRL 115, 062501 (2015).

Relic neutrino experiments

- Vergados et al.,
  ‘Prospects of detection of relic antineutrinos by
  resonant absorption in electron capturing nuclei.’
  [J. Phys. G. Phys. 41 (2014)]
  “^{157}Tb is a better candidate than ^{163}Ho.” (?)

Experimental challenging techniques

- High Precision Penning Trap Mass Spectroscopy (PT-MS)

  [Blaum et al., Contemp. Phys. 51, 149 (2010)]

  S. Eliseev et al.,'Direct Measurement of the Mass Difference of ^{163}Ho and ^{163}Dy Solves the Q-Value Puzzle for the Neutrino Mass Determination',

  PRL 115, 062501 (2015)

  - This accurately measures the mass difference between the parent and the daughter nuclei.

- Microcalorimetry

  [Gastaldo et al., Nucl. Instr. Meth. A 711, 150 (2013)]

  - This measures the de-excitation spectrum.
  - It analyzes the bolometric spectrum (γ and X-rays).
  - The expected peaks will be well separated by a precision of a few eV.
  - One hope to observe any relic antineutrino events at the tail.

Purpose

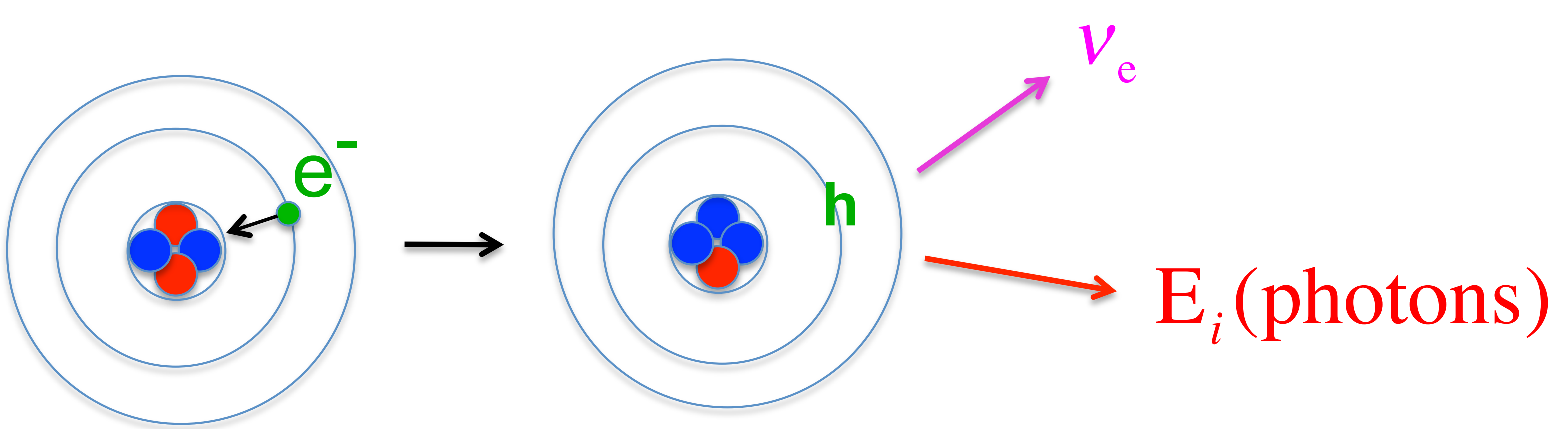
- Any other possible candidates for relic $\bar{\nu}$ capture experiment?

- Relic $\bar{\nu}$ capture by EC decaying nuclei.
  - EC decay
  - Relic $\bar{\nu}$ capture

- Apply to ^{163}Ho, ^{243}Cm, ^{157}Tb.
- Show all possible candidates for relic $\bar{\nu}$ capture experiment.

Electron Capture (EC) decay

EC : inverse beta decay



$$\boxed{(A,Z) \rightarrow (A,Z-1)^* + \nu_e \rightarrow (A,Z-1) + E_i + \nu_e}$$

E_i : de-excitation energy of i-th atomic shell (K,L,M,..), corresponding to the electron hole B.E. of the daughter atom → measurable!

Reaction rate for EC decay

$$(A,Z) \rightarrow (A,Z-1)^{*} + \nu_{\mathrm{e}} \rightarrow (A,Z-1) \;\; + \mathrm{E}_i + \nu_{\mathrm{e}}$$

$$\boxed{\lambda_{EC} = \frac{G_\beta^2}{4\pi^2} \sum_i n_i C_i \beta_i^2 B_i (Q - E_i) \sqrt{(Q - E_i)^2 - m_\nu^2}}$$

$$G_\beta = G_F \cos\theta_C$$

n_i : fraction of occupancy of the *i*-th atomic shell

C_i : nuclear shape factor (~all equal in an allowed transition)

β_i : Coulomb amplitude of electron radial wave function

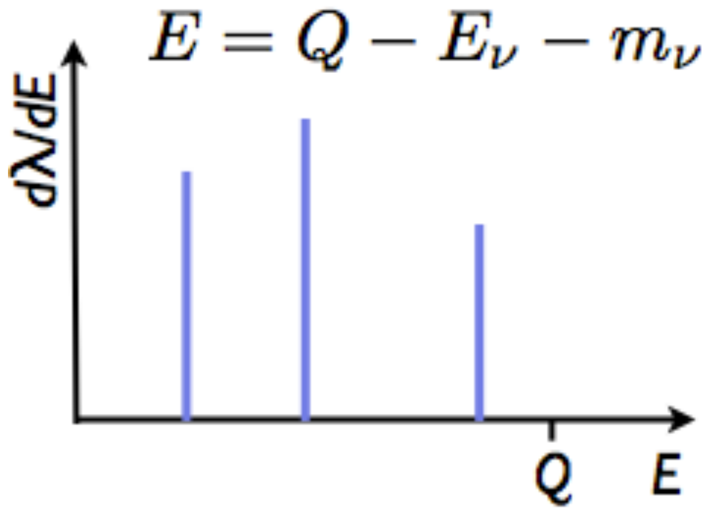
B_i : atomic correction for electron exchange and overlap (~1)

Discrete energy spectrum

- In principle, the energy spectrum is given by a series of lines.

$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q - E_c)\sqrt{(Q-E_c)^2 - m_\nu^2}$$
$$\times \sum_i n_i C_i \beta_i^2 B_i \delta(E_c - E_i)$$

$(E_c :$ Calorimetric energy$)$



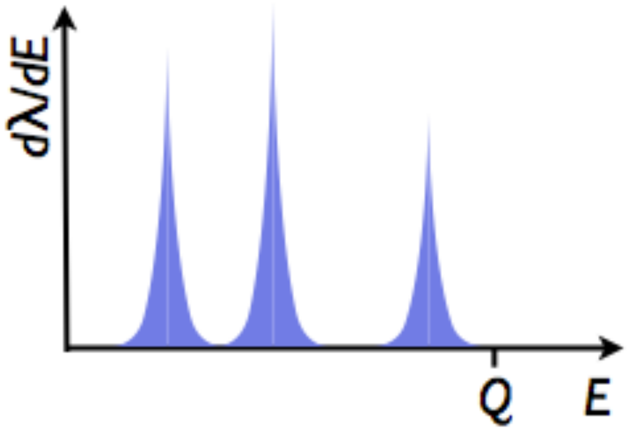
- The δ - ft. does not allow to measure the spectrum endpoint.
- EC is not sensitive to neutrino mass features at the endpoint.

Uncertainty relation

- Atomic levels have finite widths.
  → δ-function should be replaced by a Breit-Wigner.
  (De Rùjula, Lusignoli, 1982)

$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2}$$

$$\times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$

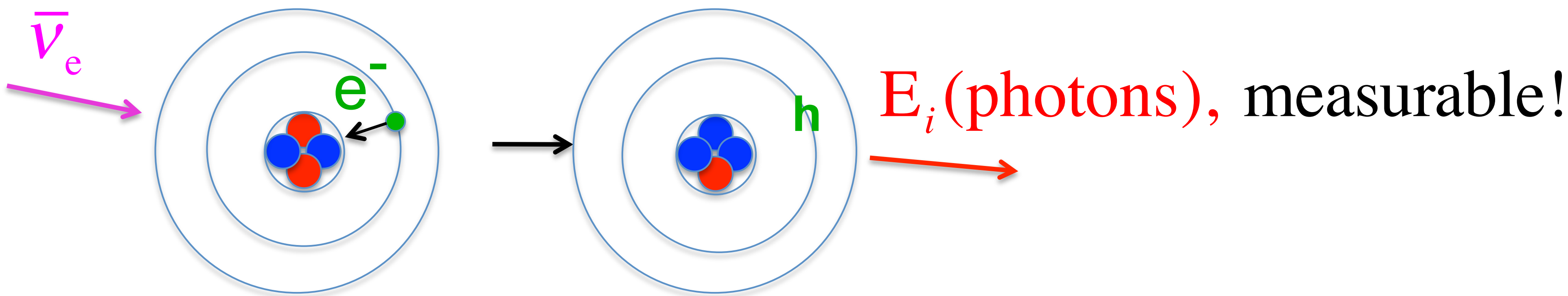


- This allows E to reach the Q-value and to produce a neutrino with zero energy.
- One needs a nucleus with an E_i close to Q-value to have small suppression from the Breit-Wigner.

Relic $\bar{\nu}_e$ capture

Relic $\bar{\nu}_e$ capture by EC decaying nucleus

- The crossed reaction with an incoming $\bar{\nu}_e$ has no energy threshold.
- The nucleus can absorb the $\bar{\nu}_e$ with zero energy.



$$\boxed{\bar{\nu}_e + (A,Z) \rightarrow (A,Z-1)^* \rightarrow (A,Z-1) + E_i}$$

E_i : de-excitation energy of i-th atomic shell (K,L,M,..)

→ measurable!

Reaction rate for $\bar{\nu}_e$ capture

$$\bar{\nu}_e + (A,Z) \rightarrow (A,Z-1)^* \rightarrow (A,Z-1) + \mathrm{E}_i$$

$$\boxed{\lambda_{\bar{\nu}} = n_{\bar{\nu}} \frac{G_\beta^2}{2} \sum_i n_i C_i \beta_i^2 B_i \rho_i(E_{\bar{\nu}})}$$

$G_\beta = G_F \cos\theta_C$

$n_{\bar{\nu}} (= n_\nu)$: # density of incoming $\bar{\nu}$'s ($\sim 55/\mathrm{cm}^3$)

$E_{\bar{\nu}}$: energy of incoming relic $\bar{\nu}$'s ($\simeq m_\nu$ for CνB)

β_i : Coulomb amplitude of electron radial wave function

B_i : atomic correction for electron exchange and overlap($\sim$1)

$\rho_i(E_{\bar{\nu}})$: density of final state per energy (Breit-Wigner form)

Interaction rate of relic $\bar{\nu}_e$ and EC

$$\boxed{\frac{\lambda_{\bar{\nu}}}{\lambda_{EC}} \simeq 2\pi^2 n_{\bar{\nu}} \frac{\sum_i n_i \beta_i^2 B_i \rho_i(E_{\bar{\nu}})}{\sum_i n_i \beta_i^2 B_i (Q - E_i)^2}}$$

$n_{\bar{\nu}}(= n_\nu)$: # density of incoming $\bar{\nu}$'s (~ 55/cm^3)

n_i : fraction of occupancy of i-th atomic shell

β_i : Coulomb amplitude of electron radial wave function

B_i: atomic correction for electron exchange and overlap (~1)

$\rho_i(E_{\bar{\nu}})$: density of final state per energy

Application to ^{163}Ho

- **^{163}Ho**

  - $T_{1/2}$: 4570 ± 25 y
  - Q_{EC}: 2.80 ± 0.05 keV (Gatti et al., 2008)

    2.555 ± 0.016 keV (Reich & Singh, 2011)

    2.833(30_{stat})(15_{sys}) keV (Eliseev et al., 2015)

- EC decay of ^{163}Ho

$$\boxed{{}^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*}_{i} + \nu_{\mathrm{e}} \rightarrow {}^{163}_{66}\mathrm{Dy} + \mathrm{E}_{i} + \nu_{\mathrm{e}}}$$

- Relic $\bar{\nu}_{\mathrm{e}}$ capture on ^{163}Ho

$$\boxed{\bar{\nu}_{\mathrm{e}} + {}^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*}_{i} \rightarrow {}^{163}_{66}\mathrm{Dy}_{i} + \mathrm{E}_{i}}$$

Application to ^{163}Ho

The Q -value for EC decay of $^{163}_{67}$Ho is so small that only electrons from the following levels can be captured.

Energy levels & their widths of the captured electrons, for $^{163}_{66}$Dy.

Level	E_i (eV)	Γ_i (eV)
M_1 [3S]	2047	13.2
M_2 [$3P_{1/2}$]	1842	6.0
N_1 [4S]	414.2	5.4
N_2 [$4P_{1/2}$]	333.5	5.3
O_1 [5S]	49.9	3
O_2 [$5P_{1/2}$]	26.3	3

Application to ^{163}Ho

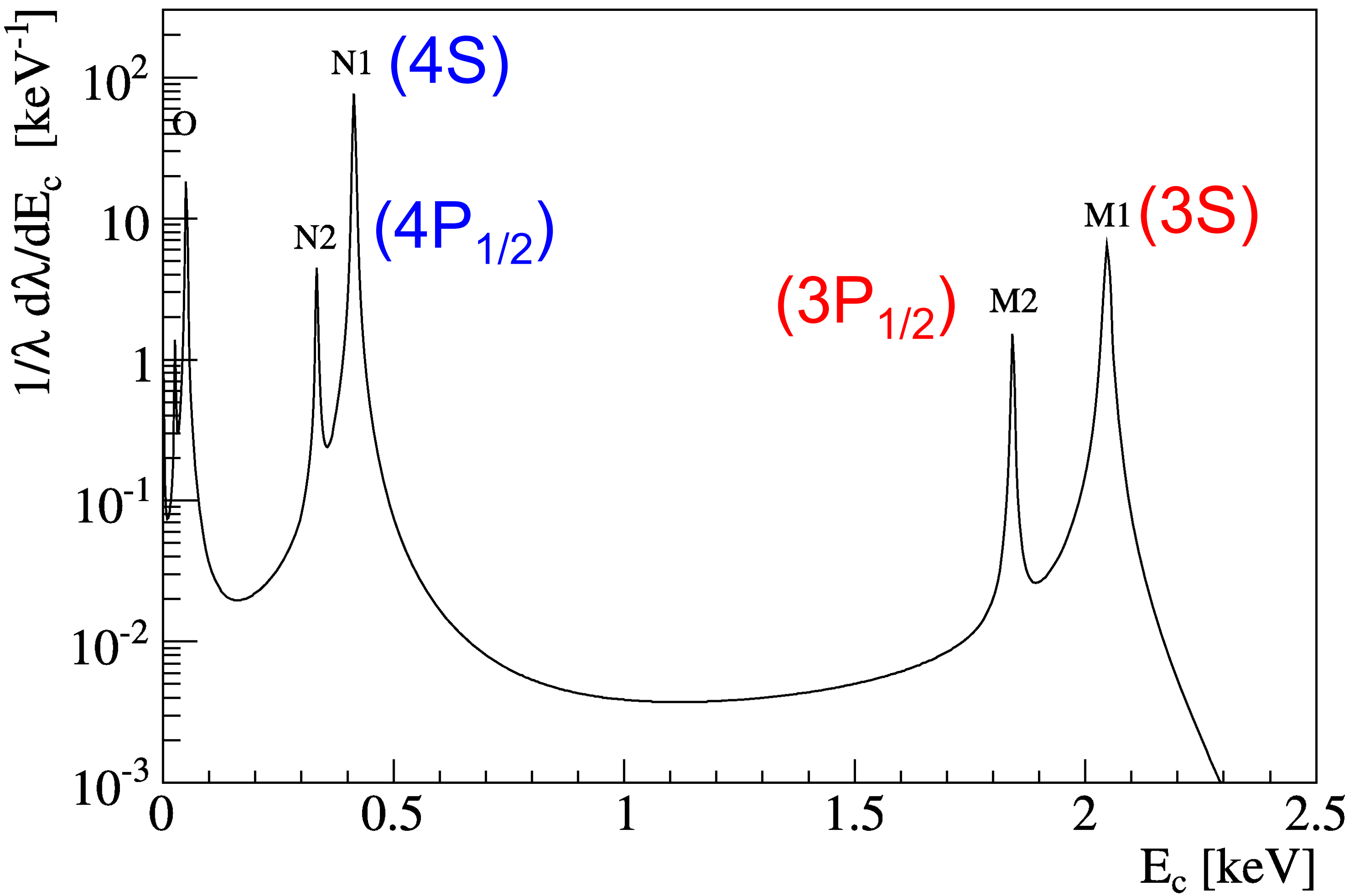
Electrons squared wave functions at the origin β_i^2 relative to β_{3S}^2
[I.M. Band et al., At. Data. Nucl. Data Tables 35, 1 (1986).]

Levels	**Ratio**
3S / 3S	1.0
$3P_{1/2}$ / 3S	0.0526
4S / 3S	0.232
$4P_{1/2}$ / 3S	0.0119
5S / 3S	0.0345
$5P_{1/2}$ / 3S	0.0015
6S / 3S	0.0021

For given principle quantum number,
electron squared wave function of S-state (l=0) is
much larger than the one of $P_{1/2}$ state.

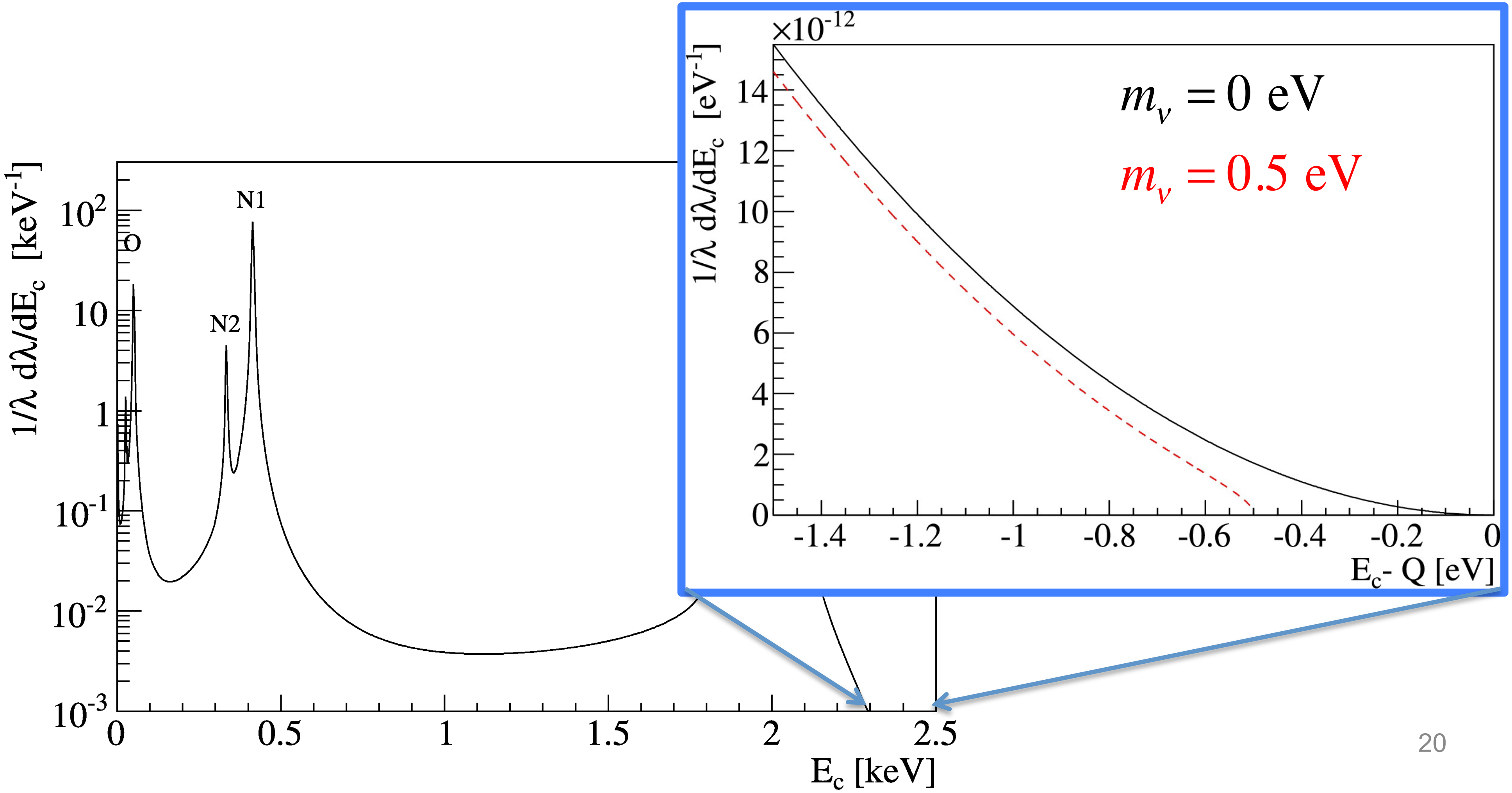
Application to ^{163}Ho

Energy spectrum in EC decays of ^{163}Ho [Q=2.5 keV]
→ De-excitation energy spectrum of ^{163}Dy*



Application to ^{163}Ho

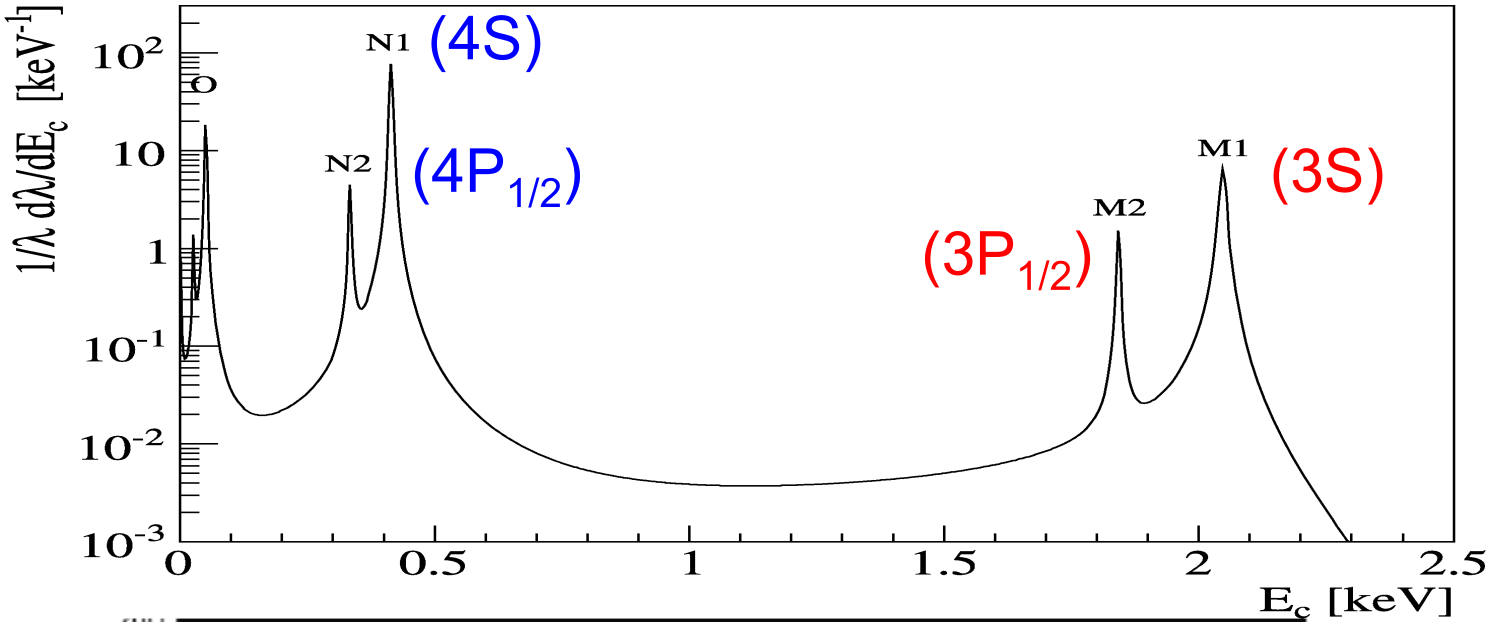
Energy spectrum in EC decays of ^{163}Ho [Q=2.5 keV]
→ De-excitation energy spectrum of ^{163}Dy*



Application to ^{163}Ho

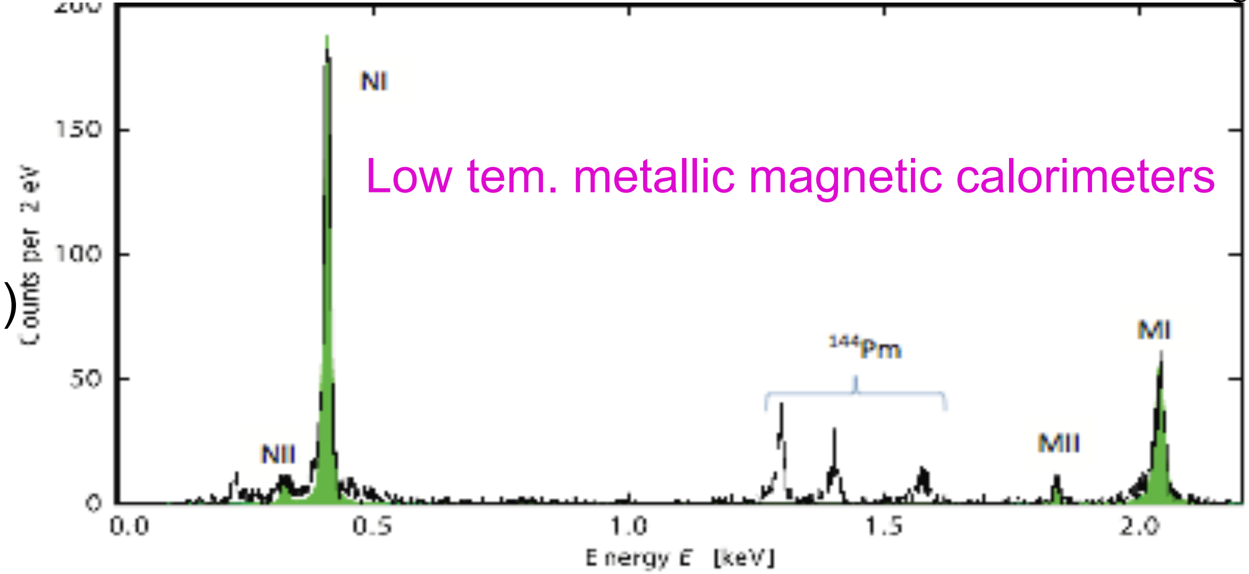
De-excitation energy spectrum of ^{163}Dy*

Calculation



Experiment

Blaum et al.
(arXiv:1306.2655v1)



Application to ^{163}Ho

Interaction rate for ^{163}Ho

$$\boxed{\frac{\lambda_{\bar{\nu}}}{\lambda_{EC}} \simeq 2\pi^2 n_{\bar{\nu}} \frac{\sum_i n_i \beta_i^2 B_i \rho_i(E_{\bar{\nu}})}{\sum_i n_i \beta_i^2 B_i (Q - E_i)^2}}$$

Q_{EC}: 2.80 ± 0.05 keV (Gatti et al., 2008)
2.555 ± 0.016 keV (Reich & Singh, 2011)
2.833(30_{stat})(15_{sys}) keV (Eliseev et al., 2015)

Q-value	2.2 keV	2.5 keV	2.8 keV	2.833 keV
$\lambda_{\bar{\nu}} / \lambda_{EC}$	7.6×10^{-22}	5.8×10^{-23}	1.4×10^{-23}	1.2×10^{-23}

→Very sensitive to Q-value !

<u>For Q=2.833 keV</u>

For 10 events per year → We need 1.46 ton ^{163}Ho source.

Feasibility

- If there is no overdensity $\left(= \dfrac{\rho(x) - \bar{\rho}}{\bar{\rho}} \right)$ in the ν distribution, the detection is not possible.

- Kaboth et al., [PRD82, 2010]

  "If the overdensity is > $2\text{x}10^9$,

  KATRIN experiment may be able to detect relic neutrinos"

- The overdensity is expected to be less than $\sim 10^4$, which is the matter overdensity in our galaxy.

  [Ringwald & Wong, JCAP 0412, 005 (2004)]

Any other candidates?

- Krauss & Grashow [Nature 310, 19(1984)] & others

→ do not consider

    - decay to excited state (meta-stable state)
    - electron states with higher principal quantum numbers.

- Meta-stable state

 - $T_{1/2} > 10^{-9}$ s

 - Occasionally, $T_{1/2}$ is far longer.

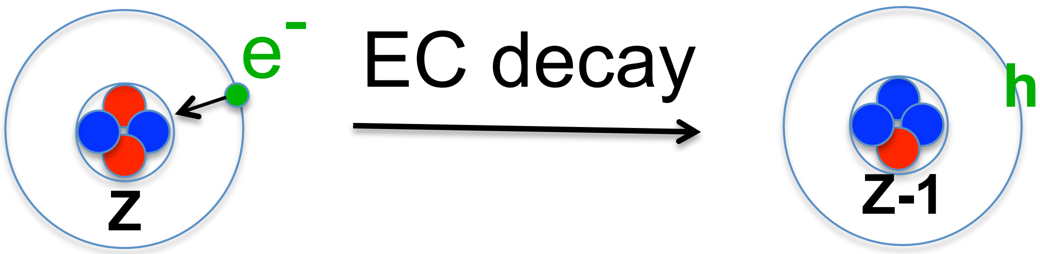
 [lasting minutes, hours, or 10^{15} years for ^{180m}Ta.]

Any other candidates?

We checked whether there would be any other candidates for the relic $\bar{\nu}$ capture experiment with calculations of Q-value for EC with allowed selection rule including

- all electron states including higher principal quantum numbers, K, L, M, N, O, P, ….
- excited states of daughter nuclei (meta-stable state)

Any other candidates?



Going to Ground State

$$Q_{EC} = \Delta m_{(Z)} - \Delta m_{(Z\text{-}1)}' \quad (\,'\,\text{: atomic excitation})$$

$$= \Delta m_{(Z)} - \left[\Delta m_{(Z-1)} + B_{(Z-1).e} - B_{(Z-1).e-last\_} \right]$$

$$= \Delta m_{(Z)} - \Delta m_{(Z-1)} - B_{(Z-1).e} + B_{(Z-1).e-last}$$

$$dQ_{EC} = \sqrt{\Delta m^2_{(Z)} + \Delta m^2_{(Z\text{-}1)}}$$

- Considered EC from all electron levels, K, L,M,N,O,P, (l=0,1,2,3,4,….)
- Q_{EC} < 60 keV

Other candidates (for going to ground states)

New AME data (Audi et al., 2013)

N	Z	A	EL	MASS EXCESS		B.E. /A		DECAY	ENERGY
97	66	163	Dy	-66379.861	1.883	8161.777	0.012	β-	-2.555
96	67	163	Ho	-66377.306	1.883	8156.962	0.012	β-	-1210.729
93	64	157	Gd	-70822.822	1.623	8203.500	0.010	β-	-60.044
92	65	157	Tb	-70762.778	1.649	8198.134	0.011	β-	-1339.145
124	81	205	Tl	-23820.349	1.329	7878.392	0.006	β-	-50.632
123	82	205	Pb	-23769.717	1.239	7874.328	0.006	β-	-2705.559
148	95	243	Am	57176.315	2.266	7530.168	0.009	β-	-7.473
147	96	243	Cm	57183.788	2.052	7526.918	0.008	β-	-1507.591
116	77	193	Ir	-34538.319	1.932	7938.144	0.010	β-	-56.628
115	78	193	Pt	-34481.690	1.952	7933.797	0.010	β-	-1075.761

A new candidate – ^{243}Cm

- **$^{243}_{96}Cm$ ($\rightarrow$ $^{243}_{95}Am$)**

  - $T_{1/2}$: 29.1 ± 0.1 y
  - Q_{EC}: 7.5 ± 1.7 keV (Akovali, NNDC, 2004)

    7.473 ± 1.713 keV (Audi, 2013)

- EC decay of ^{243}Cm

$$\boxed{{}^{243}_{96}\mathrm{Cm} \rightarrow {}^{243}_{95}\mathrm{Am}^{*}_{i} + \nu_{e} \rightarrow {}^{243}_{95}\mathrm{Am} + \mathrm{E}_{i} + \nu_{e}}$$

- Relic $\bar{\nu}_e$ capture on ^{243}Cm

$$\boxed{\bar{\nu}_{e} + {}^{243}_{96}\mathrm{Cm} \rightarrow {}^{243}_{95}\mathrm{Am}^{*}_{i} \rightarrow {}^{243}_{95}\mathrm{Am} + \mathrm{E}_{i}}$$

Application to $^{243}_{96}Cm$

The Q -value for EC decay of $^{243}_{96}Cm$ is so small that only electrons from levels M1, M2, N1, N2, O1, O2, P1, P2 can be captured.

Energy levels & their widths of the captured electrons, for $^{243}_{95}Am$.

Level	E_i (eV)	Γ_i (eV)
M_1 [3S]	6133.0	16 [from ^{92}U]
M_2 [$3P_{1/2}$]	5739.0	15 [from ^{92}U]
N_1 [4S]	1620.3	13 [from ^{92}U]
N_2 [$4P_{1/2}$]	1438.0	12 [from ^{93}Np]
O_1 [5S]	365.0	3
O_2 [$5P_{1/2}$]	298.0	2
P_1 [6S]	48.0	1
P_2 [$6P_{1/2}$]	29.0	1

Application to $^{243}_{96}Cm$

Interaction rate for ^{243}Cm

$$\boxed{\frac{\lambda_{\bar{\nu}}}{\lambda_{EC}} \simeq 2\pi^2 n_{\bar{\nu}} \frac{\sum_i n_i \beta_i^2 B_i \rho_i(E_{\bar{\nu}})}{\sum_i n_i \beta_i^2 B_i (Q - E_i)^2}}$$

Q_{EC}: 7.5 ± 1.7 keV (Akovali, NNDC, 2004)

7.473 ± 1.713 keV (Audi, 2013)

Q-value	7.50 keV	7.47 keV	5.77 keV
$\lambda_{\bar{\nu}} / \lambda_{EC}$	6.88×10^{-25}	7.24×10^{-25}	3.44×10^{-22}

(Cf) ^{163}Ho : 1.2×10^{-23}, for Q_{EC}=2.833 keV

Any other candidates?

Are there other candidates for the relic $\bar{\nu}$ capture experiment?

i) Consider EC from all electron states, K, L, M, N, O, P…

ii) Consider EC decay leading to excited states of daughter nuclei expecting resonant EC decay.

$$Q'_{EC} = \Delta m_{(Z)} - \Delta m_{(Z\text{-}1)}{}^{*\prime}$$

(' : atomic excitation, *: nuclear excitation)

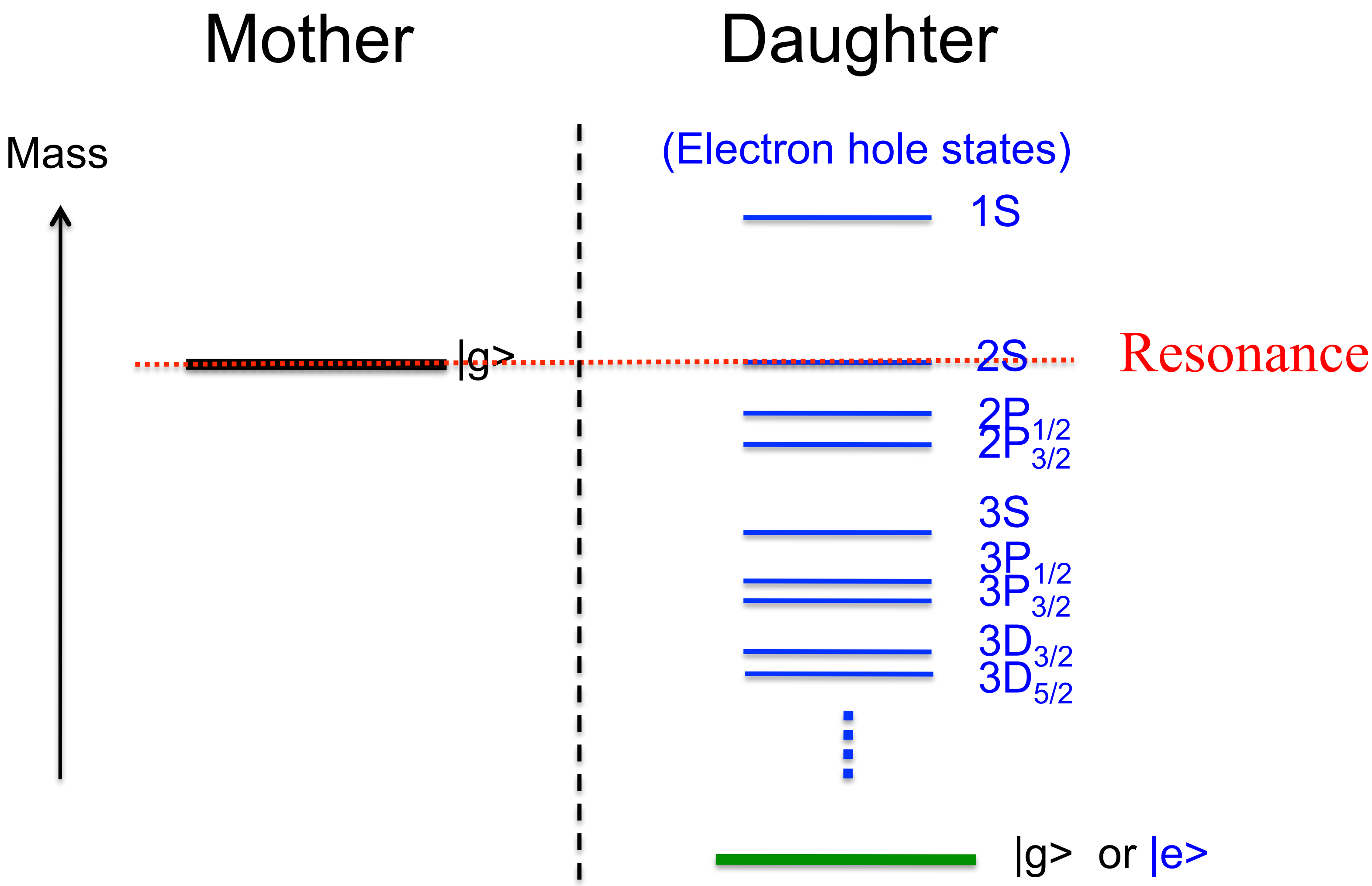
$$dQ'_{EC} = \sqrt{\Delta m^2_{(Z)} + \Delta m^2_{(Z\text{-}1)}}$$

$$\Delta Q'_{EC} = \left|Q'_{EC}\right| - dQ'_{EC}$$

Conditions: $T_{1/2}$ >10 days,

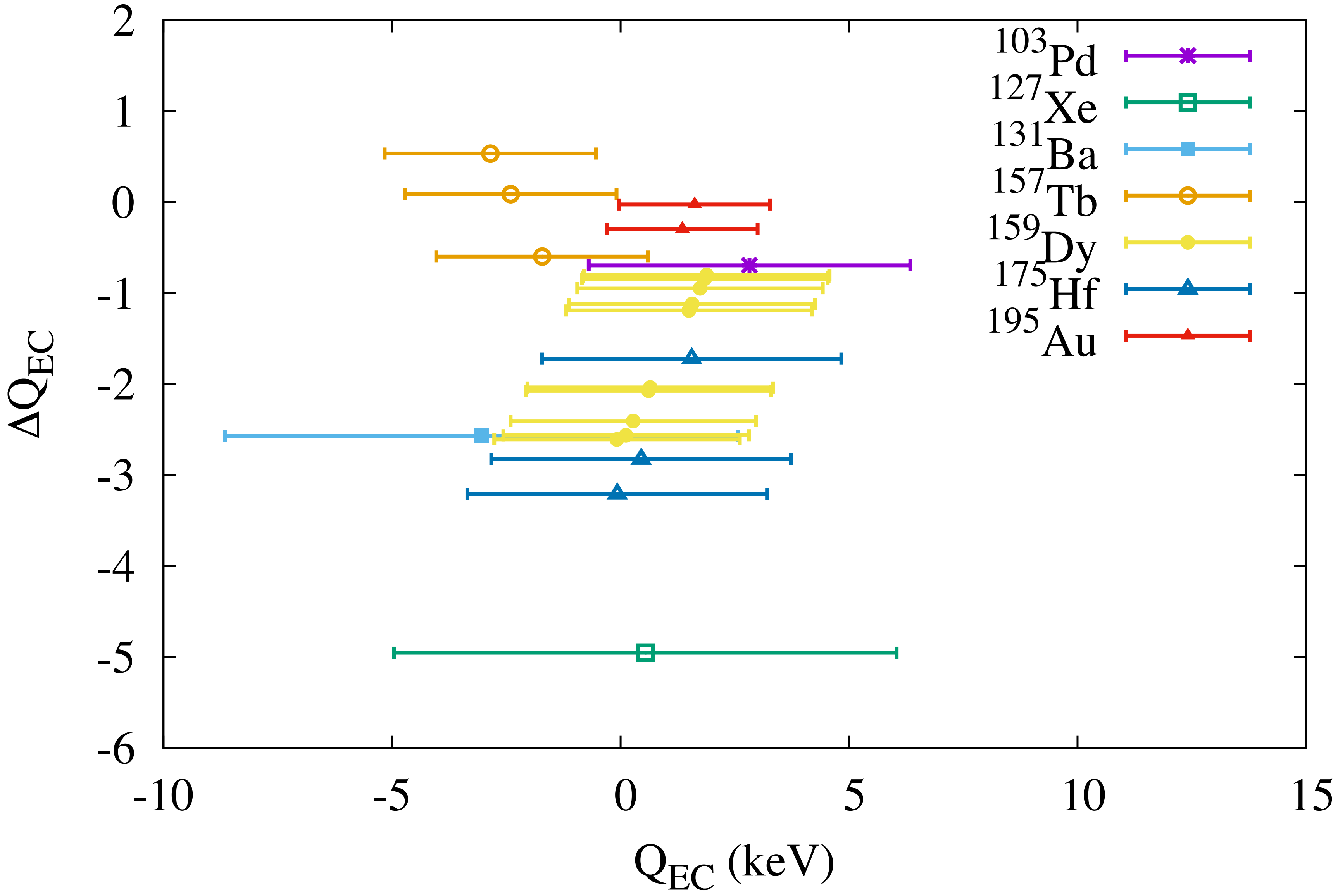
Q'_{EC}<10 keV, dQ'_{EC}<10 keV, $\Delta Q'_{EC}$<10 keV

Any other candidates?



$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2}\times\sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$

New candidates (for going to excited states)?



New candidates (for going to excited states)?

Mother	$T_{1/2}$	$J_i\Pi_i$	Daughter	$J_f\Pi_f$	E_{excited} (keV)	Q'_{EC} (keV)	dQ'_{EC} (keV)	$\Delta Q'_{EC}$ (keV)
^{103}Pd	16.991 d	5/2+	^{103}Rh	5/2+	536.8	3.231	3.517	−0.287
^{127}Xe	36.346 d	1/2+	^{127}I	3/2+	628.7	0.544	5.496	−4.952
^{131}Ba	11.50 d	1/2+	^{131}Cs	3/2 *	1342.	−3.043	5.612	−2.569
^{157}Tb	71 y	3/2+	^{157}Gd	5/2−	54.53	1.714	2.314	−0.600
^{159}Dy	144.4 d	3/2−	^{159}Tb	5/2−	363.5	−0.078	2.686	−2.608
^{175}Hf	70 d	5/2−	^{175}Lu	(7/2−)	672.9	−0.070	3.278	−3.208
^{195}Au	180.098 d	3/2+	^{195}Pt	1/2−	222.2	1.353	1.648	−0.295

(* 1/2+ , GEANT4 data)

$$Q'_{EC} = \Delta m_{(Z)} - \Delta m_{(Z\text{-}1)}{}^{*'}$$ (' : atomic excitation, *: nuclear excitation)

$$dQ'_{EC} = \sqrt{\Delta m^2_{(Z)} + \Delta m^2_{(Z\text{-}1)}}\ , \quad \Delta Q'_{EC} = \left|Q'_{EC}\right| - dQ'_{EC}$$

Any other candidates?

- Vergados et al.,

  'Prospects of detection of relic antineutrinos by resonant absorption in electron capturing nuclei.'

  [J. Phys. G. Phys. 41 (2014)]

" ^{157}Tb is a better candidate than ^{163}Ho." (?)

A new candidate - ${}^{157}_{65}\mathrm{Tb}$

- **${}^{157}_{65}\mathrm{Tb}$ ($\rightarrow$ ${}^{157}_{64}\mathrm{Gd}$)**

  - $T_{1/2}$: 71 ± 7 y (NNDC, 2004)

  - Q_{EC}: 60.044 ± 0.297 keV (Audi, 2012)

    60.1 ± 0.3 keV (Helmer, NNDC, 2004)

- EC decay of ${}^{157}\mathrm{Tb}$

$$\boxed{{}^{157}_{65}\mathrm{Tb} \rightarrow {}^{157}_{64}\mathrm{Gd}^{*}_{i} + \nu_{\mathrm{e}} \rightarrow {}^{157}_{64}\mathrm{Gd} + \mathrm{E}_{i} + \nu_{\mathrm{e}}}$$

- Relic $\bar{\nu}_{\mathrm{e}}$ capture on ${}^{157}\mathrm{Tb}$

$$\boxed{\bar{\nu}_{\mathrm{e}} + {}^{157}_{65}\mathrm{Tb} \rightarrow {}^{157}_{64}\mathrm{Gd}^{*}_{i} \rightarrow {}^{157}_{64}\mathrm{Gd} + \mathrm{E}_{i}}$$

Application to $^{157}_{65}Tb$

The Q -value for EC decay of $^{157}_{65}Tb$ is so small that only electrons from the following levels can be captured.

Energy levels & their widths of the captured electrons, for $^{157}_{64}Gd$.

Level	E_i (eV)	Γ_i (eV)
K [1S]	50239.1	22.4
L_1 [$2P_{1/2}$]	8375.6	3.8
L_2 [2S]	7930.3	3.87
M_1 [3S]	1880.0	12.8
M_2 [$3P_{1/2}$]	1688.3	5.6
N_1 [4S]	375.8	4.90
N_2 [$4P_{1/2}$]	288.5	5.23
O_1 [5S]	36.1	3
O_2 [$5P_{1/2}$]	20.3	3

Application to ^{157}Tb

Interaction rate for ^{157}Tb (going to 54.5 keV excited state)

$$\boxed{\frac{\lambda_{\bar{\nu}}}{\lambda_{EC}} \simeq 2\pi^2 n_{\bar{\nu}} \frac{\sum_i n_i \beta_i^2 B_i \rho_i (E_{\bar{\nu}})}{\sum_i n_i \beta_i^2 B_i (Q - E_i)^2}}$$

Q_{EC}: 60.044 ± 0.297 keV (Audi, 2012)

60.1 ± 0.3 keV (Helmer, NNDC, 2004)

Q-value	5.511 keV	5.214 keV	5.808 keV
$\lambda_{\bar{\nu}} / \lambda_{EC}$	6.33×10^{-28}	5.83×10^{-28}	7.21×10^{-28}

(Cf) ^{163}Ho : 1.2×10^{-23}, for Q_{EC}=2.833 keV

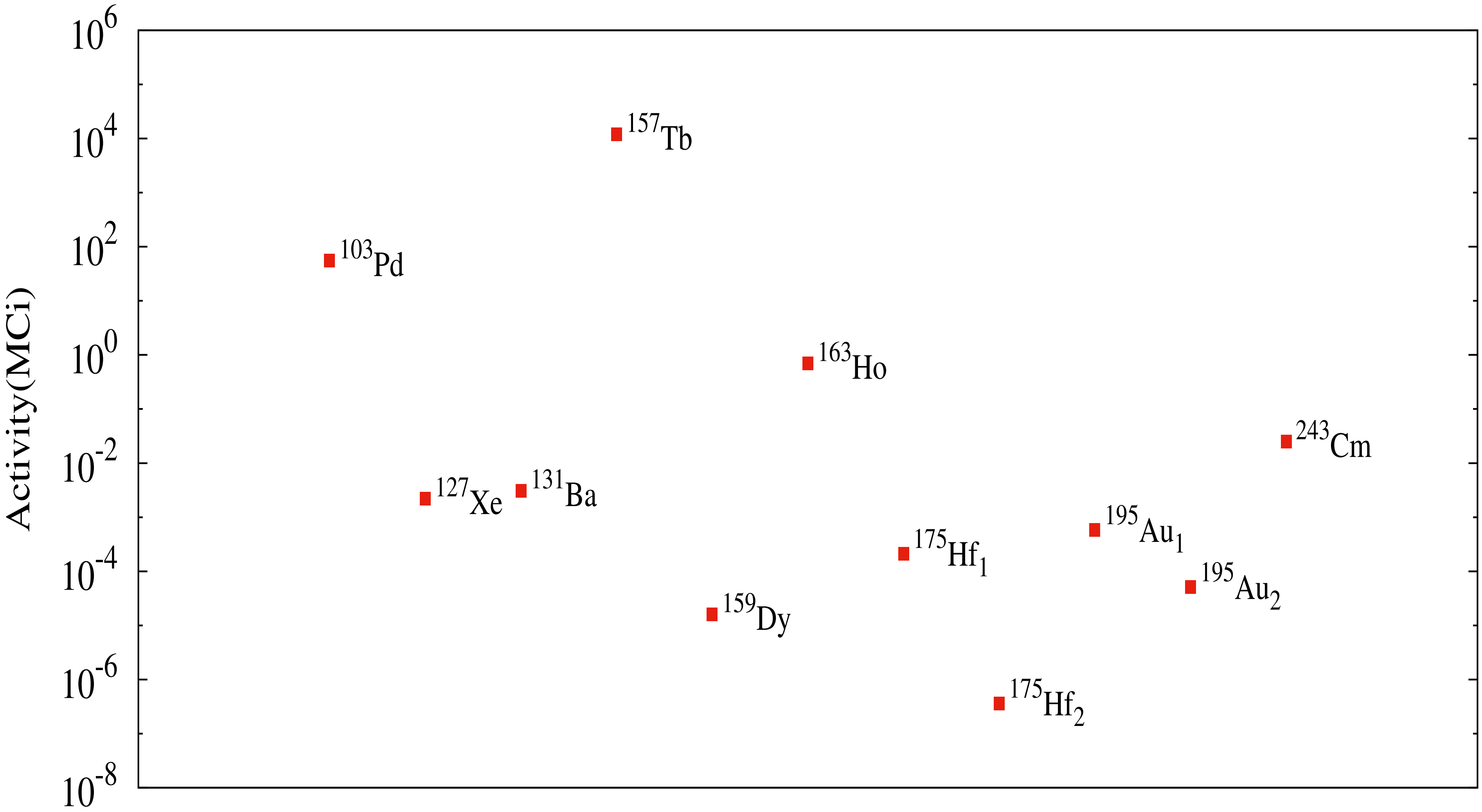
New possible candidates

For 10 events per year

Mother	$T_{1/2}$	Daughter	$E_{excited}$ (keV)	$T_{1/2}$ (ps)	$\lambda_{\bar{\nu}}/\lambda_{EC}$	Amount (kg)	Activity (MCi)
^{103}Pd	16.991 d	^{103}Rh	536.8	39	1.56×10^{-25}	7.4×10^{-1}	5.5×10^{1}
^{127}Xe	36.346 d	^{127}I	628.7	1.9	5.47×10^{-25}	7.9×10^{-5}	2.2×10^{-3}
^{131}Ba	11.50 d	^{131}Cs	1342.	-	2.96×10^{-26}	3.6×10^{-5}	3.1×10^{-3}
^{157}Tb	71 y	^{157}Gd	54.53	130	7.21×10^{-28}	370 t	1.2×10^{4}
^{159}Dy	144.4 d	^{159}Tb	363.5	153	2.62×10^{-21}	2.7×10^{-6}	1.6×10^{-5}
^{163}Ho	4570 y	^{163}Dy	g.s.	Stable	1.22×10^{-23}	1.5×10^{3}	7.0×10^{-1}
^{175}Hf$_1$	70 d	^{175}Lu	672.9	-	1.98×10^{-21}	2.0×10^{-5}	2.1×10^{-4}
^{175}Hf$_2$	70 d	^{175}Lu	684.3	-	2.25×10^{-17}	3.4×10^{-8}	3.6×10^{-7}
^{195}Au$_1$	180.098 d	^{195}Pt	211.4	49	9.96×10^{-25}	1.6×10^{-4}	5.8×10^{-4}
^{195}Au$_2$	180.098 d	^{195}Pt	222.2	-	1.99×10^{-24}	1.4×10^{-5}	5.1×10^{-5}
^{243}Cm	29.1 y	^{243}Am	g.s.	7370 y	3.44×10^{-22}	4.9×10^{-1}	2.5×10^{-2}

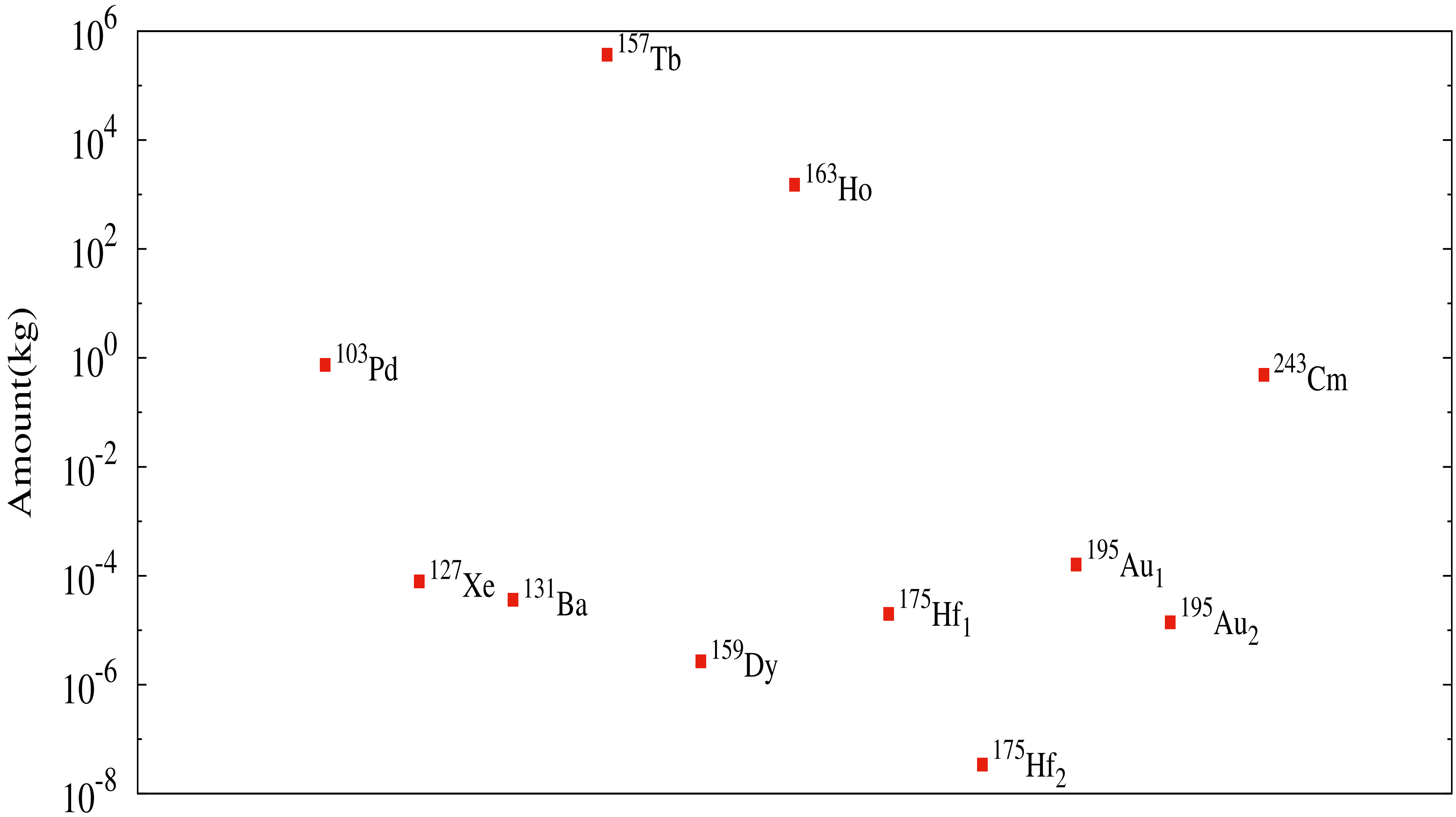
All candidates

For 10 events per year



All candidates

For 10 events per year



Conclusions

- EC decaying nuclei can capture relic $\bar{\nu}$'s.
- However, the relic $\bar{\nu}$ capture experiment is impossible for given overdensity in the $\bar{\nu}(\nu)$ distribution, which is expected to be less than $\sim 10^4$ in our galaxy.
- We found other possible candidate nuclides with resonant EC decaying nuclides for CvB detection considering EC from all electron states including higher princi pal quantum numbers, K, L, M, N, O, P, ….

- EC going to ground state ; $^{163}_{67}Ho$, ($^{243}_{96}Cm$)
- EC leading to excited state of daughter nuclei ;

$^{103}_{46}Pd$, $^{127}_{54}Xe$, $^{131}_{56}Ba$, $\cancel{^{157}_{52}Tb}$, $^{159}_{66}Dy$, $^{175}_{72}Hf$, $^{195}_{79}Au$.

THANK YOU !!