# EC induced by antineutrinos

Jeong-Yeon LEE & Yeongduk KIM

Sejong University

# Introduction

- ν's are one of the most abundant components of the universe.
- 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 matter within the first 10s after the Big Bang.
- These relic ν's may have played a crucial role in nucleo-synthesis, structure formation and the evolution of the universe as a whole.

# Introduction

- A non-zero neutrino mass can dramatically change the properties of the relic neutrino sea and its role in the evolution of the universe.
- The low E nuclear β or EC decays are excellent tools for testing non-zero ν masses.
- Among all β unstable nuclides, $^{3}H(\beta^{-})$, $^{187}Re(\beta^{-})$ & $^{163}Ho$ (EC) are attractive for (non-zero ν masses) due to their low Q-values.
- Recently the interest on the $^{163}Ho$ has been renewed.

# Introduction

- M. Lusignoli & M. Vignati

  “Relic anti-v capture on $^{163}$Ho decaying nuclei”

  [ PLB 697, 11 (2011) & PLB 701, 673 (2011) (E) ]

- Y.F. Li & Z. Xing

  “A possible detection of the cosmic anti-v background in the presence of flavor effects “

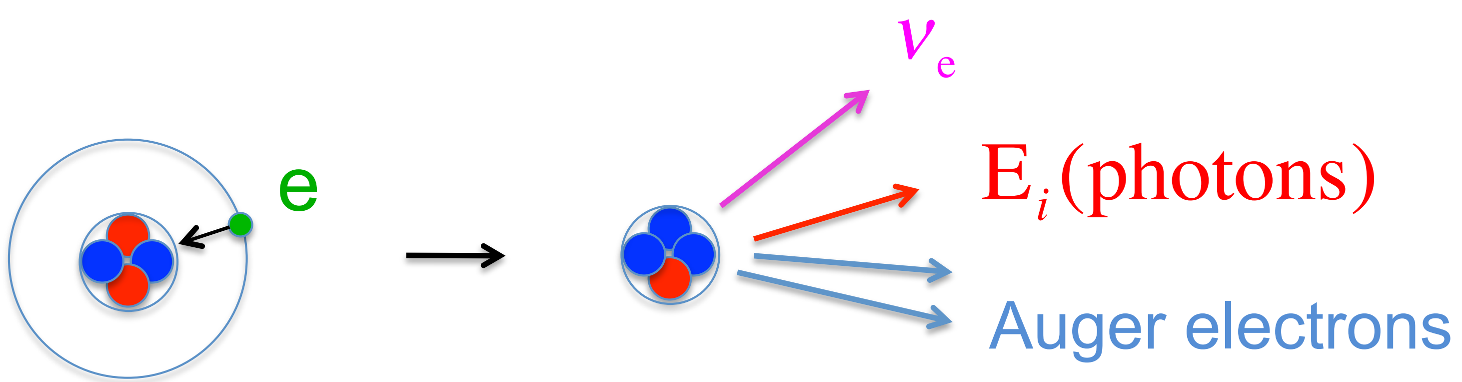
  [ PLB 698, 430 (2011) ]

# Introduction

- ‘Relic anti-v captures on EC decaying nuclei’?
- Application to $^{163}$Ho.
- Any other possible candidate nuclides?

# Electron Capture (EC) decay

EC : inverse beta decay




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

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

measurable!

# Reaction rate for EC decay

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

$$\lambda_{EC} = \frac{G_{\beta}^{2}}{4\pi^{2}} \sum_{i} n_{i} C_{i} \beta_{i}^{2} B_{i} (Q - E_{i}) \sqrt{(Q - E_{i})^{2} - m_{\nu}^{2}}$$

$G_{\beta} = G_{F} \cos\theta_{C}$

$n_{i}$ : fraction of occupancy of the $i$ - $th$ atomic shell

$C_{i}$ : nuclear shape factor

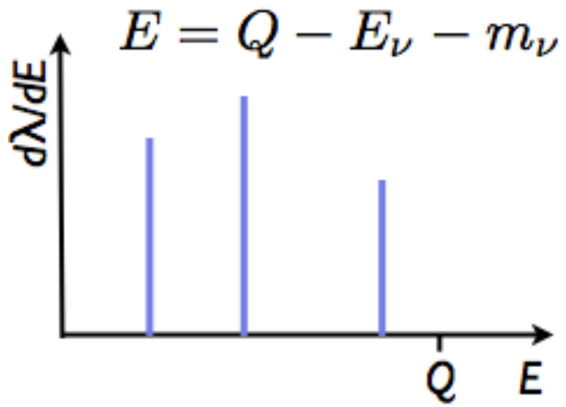
$\beta_{i}$ : Coulomb amplitude of electron radial w.f.

$B_{i}$: atomic correction for electron exchange and overlap (~1)

# Discrete energy spectrum

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

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



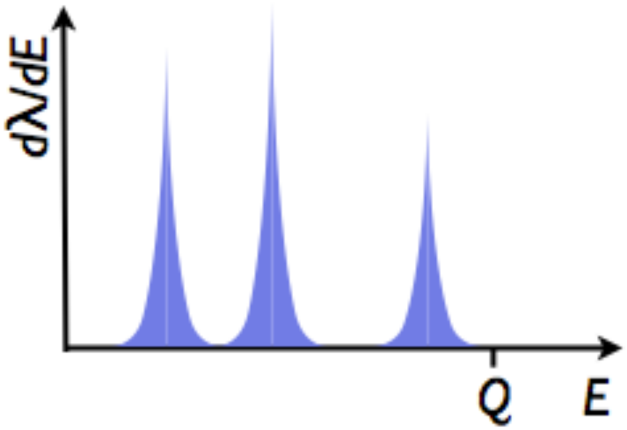

- The δ - ft. does not allow to measure the spectrum endpoint.
- EC is not sensitive to neutrino mass features at the endpoint.

# Uncertainty relation

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

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

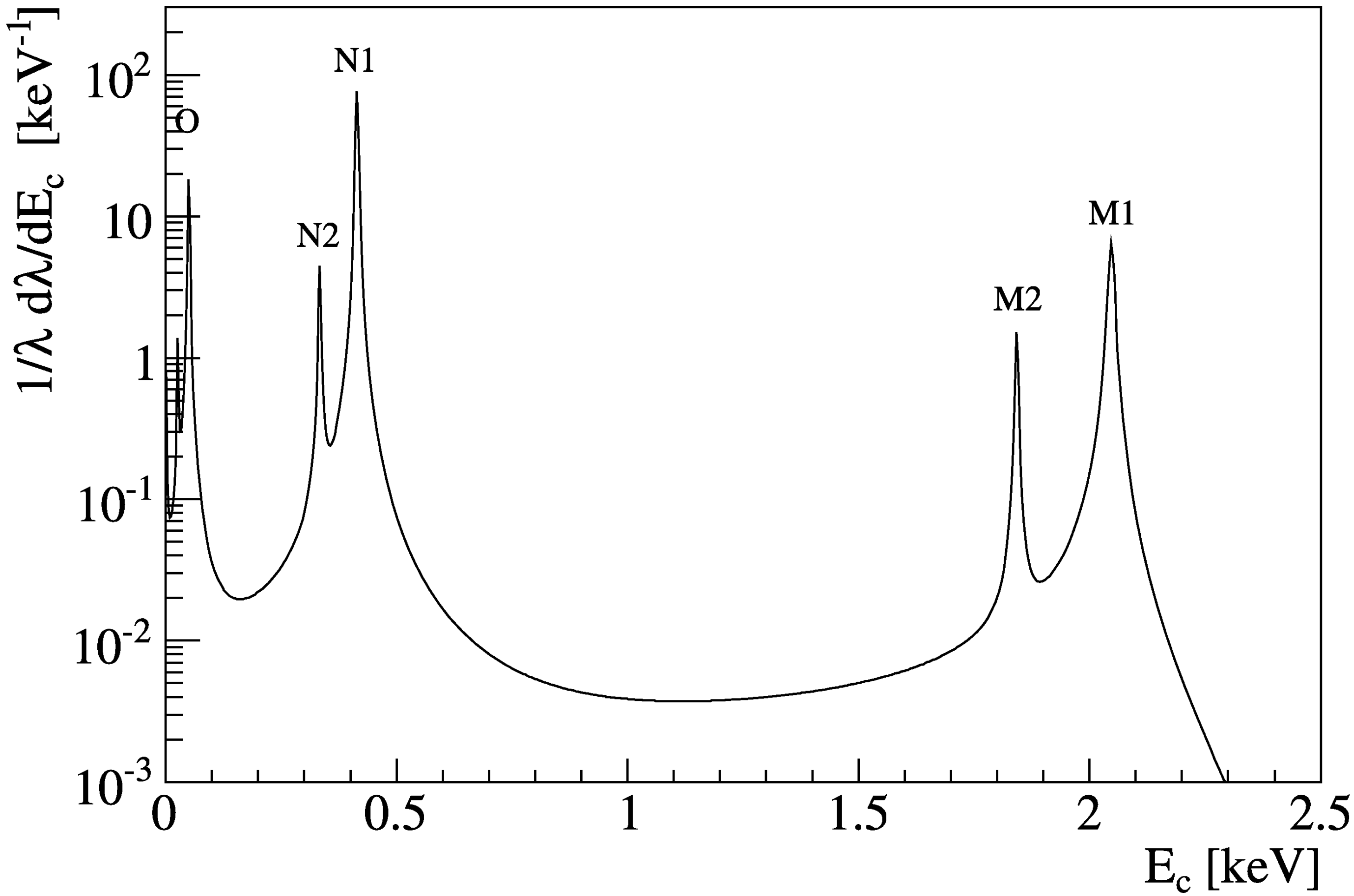
$$\times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2 / 4}$$




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

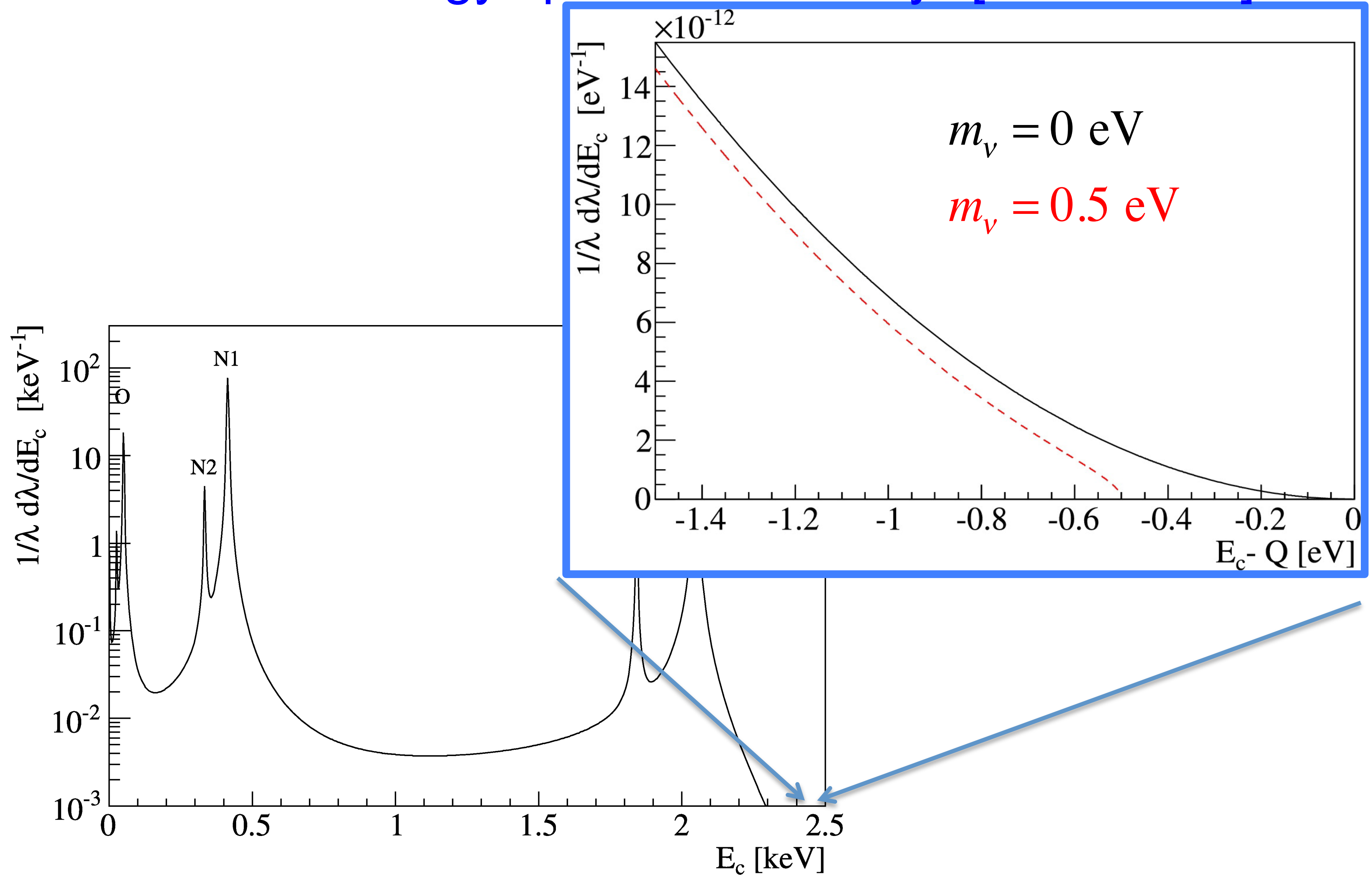
# Energy spectrum in EC decays

De-excitation energy spectrum of $^{163}Dy^*$ [Q=2.5 keV]



# Energy spectrum in EC decays

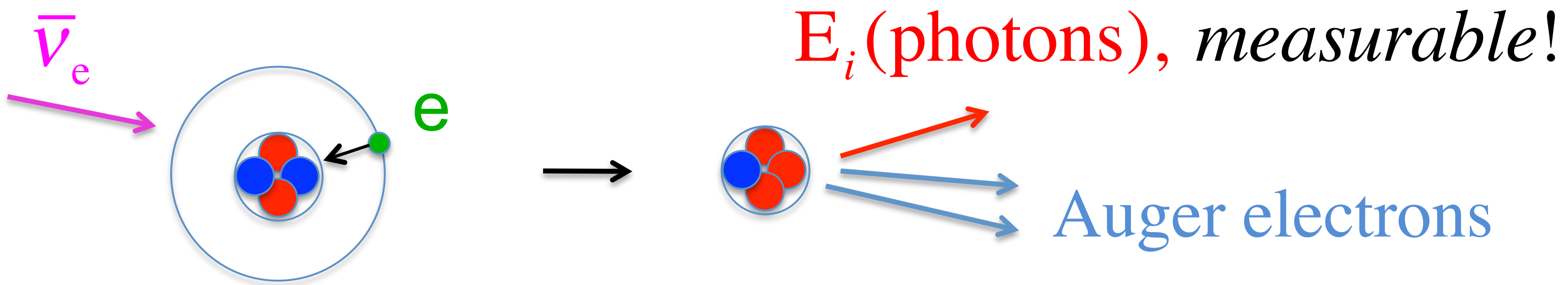
De-excitation energy spectrum of $^{163}$Dy* [Q=2.5 keV]



# Relic $\bar{\nu}_e$ capture

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

[ No energy threshold → can absorb $\bar{\nu}_e$ with zero energy. ]




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

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

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

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

$G_\beta = G_F \cos\theta_C$

$n_{\bar{\nu}} (= n_\nu)$ : # 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 C$\nu$B)

$\beta_i$ : Coulomb amplitude of electron radial w.f.

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

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

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

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

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

$n_i$ : fraction of occupancy of i-th atomic shell

$\beta_i$ : Coulomb amplitude of electron radial w.f.

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

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

# Interaction rate for $^{163}$Ho

- **$^{163}$Ho**

  - $T_{1/2}$ : 4570 y
  - Q-value for EC : 3.00 keV (NNDC at BNL)

    [ * Recent : 2.80±0.05 keV (Gomez, 2008) ]

- EC decay in $^{163}$Ho

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

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

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

# Application to $^{163}$Ho

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

| Level | $E_i$ (eV) | $\Gamma_i$ (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 |
| $P_1$ [6S] | 0.0 | 1 |

# Application to $^{163}$Ho

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

| Levels | Ratio |
|---|---|
| $3P_{1/2}$ / 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 Q.#.,
electron squared w. f. of S-state ($l$=0) is ~ 20 times larger than the one of $P_{1/2}$ state

# Application to $^{163}$Ho

Interaction rate for $^{163}$Ho

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

| Q-value | 2.2 keV | 2.5 keV | 2.8 keV |
| --- | --- | --- | --- |
| $\lambda_{\bar{\nu}} / \lambda_{EC}$ | $7.6\times10^{-22}$ | $5.8\times10^{-23}$ | $1.4\times10^{-23}$ |

# Feasibility

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

- Kaboth et al., [ PRD82, 2010, KATRIN experiment ]
  "If the overdensity is > $2 \times 10^9$,
  KATRIN experiment may be able to detect relic neutrinos"

# Any other candidates?

## Information for searching

- ‘stable.dat’ : A, element, Z, mass excess, $J^{\pi}$, $T_{1/2}$,
  decay mode, decay branch, decay Q-value.

- ‘nudat78.tab’ : abundance

- ‘element-abundance.dat’ : element abundance

- ’e_BE.dat’ : electron binding energy

# Any other candidates?

## Conditions for candidates for resonant EC

- Q-value <10 keV
- Abundance < 0.1% (should exist)
- $T_{1/2}$ of daughter nuclei (z-1) <100 y
- Selection rule allowed : $\Delta J=1$, $\Pi_f \Pi_i=+1$

# Any other better candidates?

## Resonant Capture of orbital electron of K & L shells

**G->G : L-shell EC decay**

| A | Z | life(z) | d-mode | jpia | abun(z) | Q_EC (keV) |
|---|---|---|---|---|---|---|
| 157 TB | 65 | 0.2239E+10 | EC | 3/2+ | 0.000000 | 60.00 |
| 163 HO | 67 | 0.1441E+12 | EC | 7/2- | 0.000000 | 3.00 |
| 187 OS | 76 | 0.0000E+00 | | 1/2- | 1.600000 | -3.00 |
| 193 PT | 78 | 0.1577E+10 | EC | 1/2- | 0.000000 | 57.00 |
| 194 HG | 80 | 0.1400E+11 | EC | 0+ | 0.000000 | 40.00 |
| 202 PB | 82 | 0.1656E+13 | A | 0+ | 0.000000 | 50.00 |
| 205 PB | 82 | 0.4825E+15 | EC | 5/2- | 0.000000 | 51.00 |
| 213 AT | 85 | 0.1250E-06 | A | 9/2- | 0.000000 | 73.00 |
| 215 RN | 86 | 0.2300E-05 | A | 9/2+ | 0.000000 | 82.00 |
| 243 CM | 96 | 0.9177E+09 | EC | 5/2+ | 0.000000 | 8.90 |

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**G->G : K-shell EC decay**

| | | | | | | |
|---|---|---|---|---|---|---|
| 157 TB | 65 | 0.2239E+10 | EC | 3/2+ | 0.000000 | 9.76 |
| 235 NP | 93 | 0.3422E+08 | A | 5/2+ | 0.000000 | 8.09 |
| 243 CM | 96 | 0.9177E+09 | EC | 5/2+ | 0.000000 | 6.90 |

# Any other candidates?

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

→ do not consider isomer (meta-stable state)

- Meta-stable

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

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

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

Calculation of Q-value for EC with allowed selection rule for all electron states and meta-stable states

# Conclusions

- EC decaying nuclei can capture relic anti-$\nu$'s.
- However, if there is no overdensity in the $\nu$ distribution, the detection is not possible.
- Kaboth et al., "If the overdensity is > $2\times10^9$, KATRIN experiment may be able to detect relic $\nu$'s."

- Any other possible candidate nuclides with resonant EC decaying nuclides for CvB detection (considering meta-stable states & all electron states)