PROCEEDINGS OF SCIENCE

Low-Q Electron-Capture Decays of ^{95}Tc and ^{97}Tc as Candidates for Neutrino-Mass Determination

V.-A. Sevestrean,[a,b,c,*] **O. Niţescu**[a,b] **and S. Ghinescu**[a,b,c]

[a] *Centre International de Formation et de Recherche Avancées en Physique, Atomisitilor 409, Magurele, Romania*

[b] *"Horia Hulubei" National Institute of Physics and Nuclear Engineering, Reactorului 30, Magurele, Romania*

[c] *Faculty of Physics, University of Bucharest, Atomisitilor 405, Magurele, Romania*

E-mail: sevestrean.alin@theory.nipne.ro, ovidiu.nitescu@nipne.ro, stefan.ghinescu@nipne.ro

The determination of the absolute neutrino mass scale remains one of the pressing questions in modern physics, with implications for both particle physics and cosmology. In addition to β^--decay studies, electron-capture (EC) decays with low Q values offer a complementary approach. In this work, we investigate the potential of ^{95}Tc and ^{97}Tc as candidate isotopes for neutrino-mass determination, comparing their decay characteristics with the benchmark case of ^{163}Ho. Using the atomic self-consistent Dirac–Hartree–Fock–Slater (DHFS) method, we calculated the energy-release distributions for selected ground-state-to-excited-state EC transitions. Our results indicate that the ^{95}Tc transition with $Q^*_{\mathrm{EC}} = 20.52(61)$ keV most closely resembles the spectral behavior of ^{163}Ho, while the ^{97}Tc decay also exhibits promising features. However, significant uncertainties remain in both Q^*_{EC} values and transition assignments. These findings underline the importance of precision mass measurements and transition-type determinations to fully assess the suitability of these isotopes for future neutrino-mass studies.

Matrix Elements for the Double beta decay EXperiments (MEDEX2025)
23–27 June 2025
Czech Technical University in Prague, Prague, Czech Republic

*Speaker

PoS(MEDEX2025)012

1. Introduction

Neutrino oscillation experiments with atmospheric, solar, and reactor neutrinos have established that at least two neutrino mass eigenstates possess non-zero rest mass. However, these oscillations are sensitive only to differences in mass squares and not to the absolute mass scale [1–3]. Determining the absolute neutrino mass remains one of the central open questions in particle and nuclear physics, with implications extending from weak-interaction theory to cosmology.

Several approaches have been developed to constrain or measure the neutrino mass. Cosmological probes provide indirect information by exploiting the imprint of neutrinos on the cosmic microwave background and large-scale structure. Laboratory experiments, on the other hand, offer a model-independent path by studying kinematic effects in weak decays. The most direct method relies on analyzing the electron energy spectrum near the endpoint of β^- decay. The Karlsruhe Tritium Neutrino (KATRIN) experiment currently leads this effort, with a sensitivity goal of 0.2 eV and a most recent limit of $m_\beta < 0.45$ eV (90% C.L.) [4].

Another promising avenue is the study of electron-capture (EC) decays, most notably ^{163}Ho, as pursued by the ECHo [5–7], NuMECS [8] and HOLMES [9, 10] collaborations. Current results have reached limits of about 150 eV for the electron-neutrino mass [6]. In such approaches, a low Q value is essential, since it enhances the fraction of events near the endpoint region, thereby improving sensitivity [11, 12]. To date, only ^{3}H (β^- decay) and ^{163}Ho (EC) provide practical ground-state-to-ground-state decays with sufficiently low Q values for direct neutrino mass determination.

In the case of ^{95}Tc and ^{97}Tc, there are three potential low Q-value ground-state-to-excited-state (gs-to-es) EC transitions that could be used for neutrino-mass detection. To explore this potential, we have utilised the atomic self-consistent many-electron Dirac–Hartree–Fock–Slater method to predict the energy-release distributions for the EC-decay transitions in question.

2. Theoretical framework

In this work, the main theoretical framework employed to predict the energy distribution associated with the decay process is the atomic many-electron Dirac–Hartree–Fock–Slater (DHFS) self-consistent method. The adequacy of the DHFS framework for such calculations has been demonstrated in previous studies [13].

Within the DHFS approach, electron wave functions and atomic energy levels were obtained for both the parent atom in its ground state and the daughter atom in possible excited states with a vacancy in the shell from which an electron is captured. These atomic-structure calculations were carried out using the RADIAL subroutine package [14], which incorporates the DHFS.F code. The electron shell is denoted as $x = (n, \kappa)$, with n the principal quantum number and κ the relativistic quantum number. The atomic relaxation energy after capture from shell x, denoted ε_x, is determined from the refined energy conservation relation [13]:

$$\varepsilon_x = |T_{\text{g.s.}}| - |T_x|, \tag{1}$$

where $T_{\text{g.s.}}$ and T_x correspond to the total binding energies of the final atom in the ground state and in the excited state with a vacancy in shell x, respectively.

For allowed transitions, the energy distribution of an electron-capture event is expressed as a sum over all atomic shells with $\kappa = \pm 1$:

$$\rho(E) = \frac{G_\beta^2}{(2\pi)^2} C \sum_x n_x \beta_x^2 B_x S_x \, p_\nu E_\nu \, \frac{\Gamma_x/(2\pi)}{(E-\varepsilon_x)^2 + \Gamma_x^2/4}, \tag{2}$$

where B_x and S_x are the exchange&overlap and shake-up/shake-off corrections, respectively [13]. The inclusion of shake-up and shake-off corrections extends beyond the formalism of [15]. Here, E is defined as $E = Q_{\text{EC}}^* - E_\nu$ while the neutrino momentum is$p_\nu = \sqrt{E_\nu^2 - m_\beta^2}$. The Coulomb amplitude is denoted by β_x, n_x is the relative occupancy of the shell, and Γ_x is the intrinsic width of the Breit–Wigner resonance centered at ε_x [16]. The weak interaction parameters are contained in $G_\beta = G_F \cos\theta_C$, while the nuclear-structure dependence is encoded in the shape factor

$$C = \left[{}^A F_{101}^{(0)}\right]^2 = \left[-\frac{g_{\text{A}}}{\sqrt{2J_i+1}} M_{\text{GT}}\right]^2, \tag{3}$$

where M_{GT} is the Gamow–Teller nuclear matrix element [17], J_i the angular momentum of the initial nucleus, and g_A the axial-vector coupling constant.

The shape factor C being a constant for the allowed decay type, it will simplify when we plot the normalized energy distribution.

Finally, the total decay constant λ is obtained by integrating the energy distribution over the full kinematic range, $(0, Q_{\text{EC}}^* - m_\beta)$. Within the narrow-width approximation, the decay rate can be expressed in closed analytical form:

$$\lambda = \frac{G_\beta^2}{(2\pi)^2} C \sum_x n_x \beta_x^2 B_x S_x p_{\nu x} \left(Q_{\text{EC}}^* - \varepsilon_x\right), \tag{4}$$

where $p_{\nu x} = \sqrt{\left(Q_{\text{EC}}^* - \varepsilon_x\right)^2 - m_\beta^2}$.

3. Results

In Fig. 1, we compare the normalized energy distributions following low-Q electron-capture (EC) decays of ^{95}Tc and ^{97}Tc with that of the benchmark isotope ^{163}Ho. The ground-to-ground-state (gs-to-gs) Q values are 1695.92 keV for ^{95} Tc, 324.8 keV for ^{97} Tc and 2.8632 keV for ^{163} Ho. For ^{97}Tc, we investigate the decay to the 320 keV excited state of ^{97}Mo, which corresponds to a gs-to-es Q value of $Q_{\text{EC}}^* = 4.80(10)$ keV [18]. Owing to the large uncertainty in the spin-parity assignment of this level, the transition is treated here as allowed.

For ^{95}Tc, we consider two final states at 1675.4 keV and 1683.0 keV in ^{95}Mo, with corresponding effective Q values of $Q_{\text{EC}}^* = 20.52(61)$ keV and $Q_{\text{EC}}^* = 12.92(100)$ keV, respectively [19]. In the case of ^{163}Ho, only the gs-to-gs transition is examined, given its already ultra-low Q value.

A closer view of the endpoint region, where sensitivity to the neutrino mass becomes significant, is shown in Fig. 2. The comparison indicates that the ^{95}Tc transition with $Q_{\text{EC}}^* = 20.52(61)$ keV approaches the spectral behavior of ^{163}Ho most closely, followed by the ^{97}Tc decay. However, due to the relatively large Q-value uncertainty for ^{95}Tc, its normalized spectrum may even surpass that of ^{163}Ho in certain cases, as also discussed in [19]. This highlights the need for further precision measurements of the $Q^*_{\rm EC}$ values, as well as a more definitive determination of the transition type in ^{97}Tc, to assess their true potential for neutrino-mass studies.

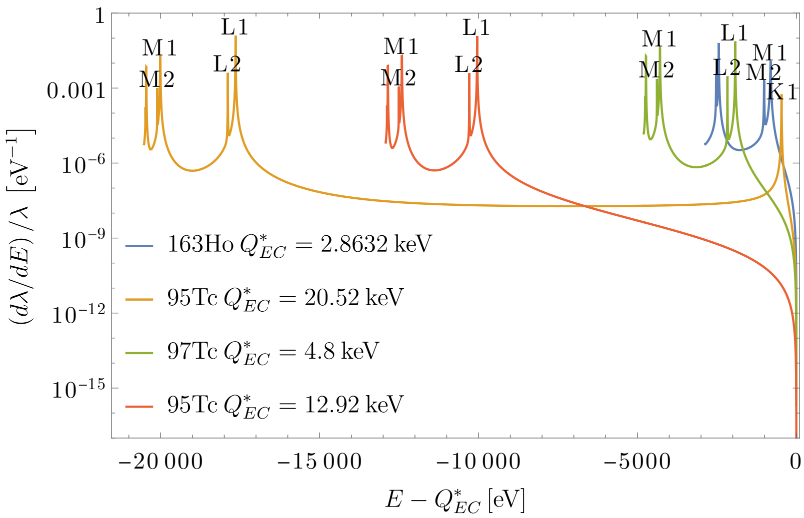

Figure 1: Normalized distributions of released energy as functions of $E - Q^*_{\rm EC}$ in the EC decay of ^{97}Tc and ^{95}Tc in the transitions to the e.s. of ^{97}Mo and ^{95}Mo and of ^{163}Ho to g.s. of ^{163}Dy. K1, L1, L2, M1, and M2 indicate subshells from which the electron was captured. The N2, N2 and O1 subshells are harder to distinguish and are not labeled.

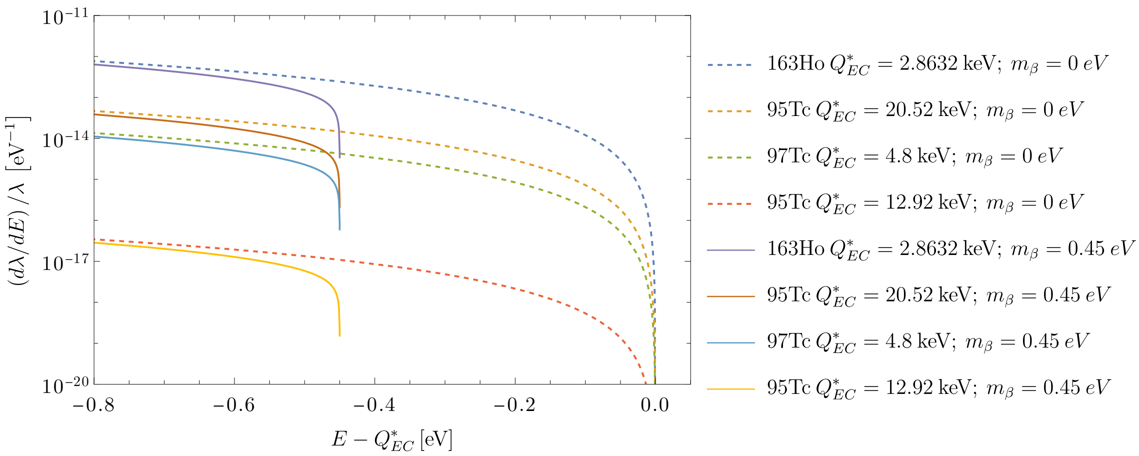

Figure 2: Zoom in near the end of the spectrum of normalized energy released distribution as functions of $E - Q^*_{\rm EC}$ of ^{97}Tc, ^{95}Tc and ^{163}Ho.

4. Conclusion

We have presented theoretical predictions for the energy-release spectra of low-Q EC decays in ^{95}Tc and ^{97}Tc and compared them to the well-established case of ^{163}Ho. The analysis demonstrates that the ^{95}Tc transition with $Q^*_{\rm EC}$ = 20.52(61) keV exhibits spectral properties that are highly comparable to ^{163}Ho, making it a candidate for further exploration. The ^{97}Tc decay, though less favorable, still shows relevant features that merit continued study.

The large uncertainties in Q^*_{EC}-values and spin-parity assignments, however, currently limit definitive conclusions. Addressing these uncertainties through high-precision Q-value measurements and improved nuclear-structure information is essential. Should these issues be resolved, ^{95}Tc and ^{97}Tc could provide valuable complementary systems to ^{163}Ho, broadening the landscape of isotopes available for direct neutrino-mass determination.

Acknowledgments

This work was supported by project PNRR-I8/C9-CF264, Contract No. 760100/23.05.2023 of the Romanian Ministry of Research, Innovation and Digitization (The NEPTUN project).

References

[1] Fukuda, Y. et al. Evidence for oscillation of atmospheric neutrinos. *Physical Review Letters* 1998;81(8):1562–1567. URL: http://link.aps.org/doi/10.1103/PhysRevLett.81.1562.

[2] SNO Collaboration. Direct Evidence for Neutrino Flavor Trans-formation from Neutral-Current Interactions in the Sudbury Neutrino Observatory. *Physical Review Letters* 2002;89(1):1–6. URL: http://dx.doi.org/10.1103/PhysRevLett.89.011301.

[3] Gerbino, M., Lattanzi, M.. Status of neutrino properties and future prospects—cosmological and astrophysical constraints. *Frontiers in Physics* 2018;5.

[4] Aker, M. et al. (KATRIN collaboration), Direct neutrino-mass measurement based on 259 days of KATRIN data, *Science* 2025;388:180-185. URL: https://www.science.org/doi/abs/10.1126/science.adq9592

[5] Gastaldo, L. et al. The electron capture in 163Ho experiment – ECHo. *European Physical Journal: Special Topics* 2017;226(8):1623–1694. URL: http://link.springer.com/10.1140/epjst/e2017-70071-y.

[6] Velte, C. et al. High-resolution and low-background 163Ho spectrum: interpretation of the resonance tails. *The European Physical Jour-nal C* 2019;79(12). URL: http://link.springer.com/10.1140/epjc/s10052-019-7513-x.

[7] Mantegazzini, et al. Development and characterisation of high-resolution microcalorimeter detectors for the echo-100k experiment. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 2023;1055:168564. URL: https://www.sciencedirect.com/science/article/pii/S0168900223005545.

[8] Croce, M. P. et al. Development of Holmium-163 Electron-Capture Spectroscopy with Transition-Edge Sensors. *Journal of Low Temperature Physics* 2016;184(3):958–968. doi: https://doi.org/10.1007/s10909-015-1451-2.

[9] Nucciotti, A. et al. Status of the HOLMES Experiment to Directly Measure the Neutrino Mass. *Journal of Low Temperature Physics* 2018;193(5-6):1137–1145.

[10] Borghesi, M. et al. An updated overview of the holmes status. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 2023;1051:168205. URL: https://www.sciencedirect.com/science/article/pii/S016890022300195X.

[11] McDonald, A.B. et al. Current direct neutrino mass experiments. *Advances in High Energy Physics* 2013;2013:293986. URL: https://doi.org/10.1155/2013/293986.

[12] Ferri, E. et al. The Status of the MARE Experiment with 187Re and 163Ho Isotopes. *Physics Procedia* 2015;61(August):227–231. URL:http://dx.doi.org/10.1016/j.phpro.2014.12.037.

[13] Sevestrean, V. A. et al. Self-consistent calculations for atomic electron capture. *Phys. Rev. A* 2023;108(1):012810. URL: https://link.aps.org/doi/10.1103/PhysRevA.108.012810.

[14] Salvat, F. et al.radial: A Fortran subroutine package for the solution of the radial Schrödinger and Dirac wave equations.*Computer Physics Communications* 2019;240:165-177. URL: https://www.sciencedirect.com/science/article/pii/S0010465519300633.

[15] Ge, Z. et al. ^{159}Dy Electron-Capture: A New Candidate for Neutrino Mass Determination. *Phys. Rev. Lett.* 2021;127(27):272301. URL: https://link.aps.org/doi/10.1103/PhysRevLett.127.272301

[16] Campbell, J.L. et al. Widths of atomic K-N7 levels. *Atomic Data and Nuclear Data Tables* 2001;77(1):1-56. URL: https://www.sciencedirect.com/science/article/pii/S0092640X00908489

[17] Behrens, H. and Bühring, W. Electron Radial Wave Functions and Nuclear Beta-decay (International Series of Monographs on Physics). Clarendon press (Oxford) 1982

[18] Ge, Z. et al. High-precision direct decay energy measurements of the electron-capture decay of ^{97}Tc. *Phys. Rev. C* 2025;112:035501. URL: https://link.aps.org/doi/10.1103/g393-xx1w.

[19] Ge, Z. et al. High-precision measurements of the atomic mass and electron-capture decay Q value of ^{95}Tc. *Physics Letters B* 2024;859:139094. URL: https://doi.org/10.1016/j.physletb.2024.139094.