# Towards Measuring the Neutrino Mass via Holmium Electron Capture Spectroscopy

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## I. EXECUTIVE SUMMARY

Experimental results from atmospheric, solar, and reactor neutrino sources have measured neutrino flavor oscillation rates and established that neutrinos have at least three mass states ($m_{\rm i}$) [1–5] . Yet neutrino oscillations are only sensitive to the differences of squared masses of different neutrino mass eigenstates. A complete picture of neutrino mass, e.g. determining all the $m_{\rm i}$, will only come from a combination of experiments in four broad classes, each sensitive to a different observable: flavor oscillations $\Delta m^2_{\rm ij}$), cosmology ($m_{\rm cos}$), searches for neutrino-less double-beta decay ($m_{\beta\beta}$), and spectroscopy of radioactive decays emitting a single neutrino or antineutrino (kinematic mass, $m_{\rm kin}$) [6–8]. Significant international effort is underway to improve mass sensitivity in each of these experimental classes. This position paper describes and discusses the prospects for an emerging alternative neutrino kinematic mass measurement method based on calorimetric electron capture spectroscopy (ECS) of $^{163}$Ho.

The ECS method is similar to the regular beta decay method in that the shape of the energy spectrum near the kinematic end point is sensitive to neutrino mass (with a similar fraction of events in the relevant endpoint region) [6, 8]. By embedding $^{163}$Ho inside low-temperature microcalorimeters, we can capture, sum and measure all the decay energy except for that of the escaping neutrino. Because the total nuclear decay energy (Q) of $^{163}$Ho is low (Q <3 keV), the spectroscopic resolution and number of events near the endpoint are matched by the technological capabilities of high-resolution sensors and large sensor arrays. Though the ECS idea was originally put forth by De Rujula and Lusignoli in 1982 [9–11], only in the last several years have the technological capabilities reached the point were this path is viable.

The central challenges for this method are isotope production and purification; incorporation of $^{163}$Ho into to sensors; high resolution spectroscopy of electron capture decays; scaling up to large array-based systems; independent measurement of Q; and a complete understanding of the nuclear and atomic physics to determine the neutrino kinematic mass. Since the last U.S. Nuclear Physics Long Range Plan (LRP) [7], significant progress has been made in all these areas. Examples of this progress include: isotope production [12, 13]; ion implantation and incorporation [14, 15]; few eV resolution for ECS and X-ray spectroscopy [14, 16–26]; both bolometric and calorimetric large-format Transition Edge Sensor (TES) arrays operating in real systems [26–30]; metallic magnetic microcalorimeters (MMCs) with high speed and competitive resolution [22, 23]; advanced microwave multiplexing techniques [31]; and a fully relativistic treatment of ECS decay including overlap and exchange corrections [32]. These results are primarily the product of three independent research teams, ECHo HOLMES , and NuMECS pursuing complementary approaches to ECS neutrino mass measurement. To build on these recent successes, now is the time for intensified efforts directed at the central challenges outlined above. The best methods for addressing these challenges are under active investigation (proton versus neutron irradiation for isotope production; MMC versus TES sensors; ion-implantation versus surface chemistry and interface metallurgy), and the three active research teams are each emphasizing different approaches to these problems.

The Collaboration to measure the Neutrino Mass via Electron Capture Spectroscopy (NuMECS) is currently an effort of several US institutions (LANL,NIST,NSCL,CMU). The overall goals of NuMECS are to critically assess the entire ECS method through experiment, theory and simulation; validate the component technologies; and demonstrate their scalability through a demonstrator experiment. In only the past two years, NuMECS has developed a complete

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process for high isotopic and elemental purity $^{163}$Ho production at the 0.1 microgram scale and demonstrated single-sensor ECS with 6 eV@6keV resolution with a surrogate isotope ($^{55}$Fe) [12, 18].

Current NuMECS sensor design is an all-silicon-body microcalorimeter sensor optimized for incorporation of radioactive materials into the absorber [17]. We are currently conducting research into methods of incorporating $^{163}$Ho into sensors at the single pixel level with emphasis on compatibility with micro-fabrication techniques. We intend to deposit the rare isotope where it is needed only (inside the pixel) so we have conservative use of $^{163}$Ho for it will always be in limited supply. We are investigating pico-liter deposition technology, surface chemistry and interface metallurgy. There is strong evidence that microstructure inside the absorber has a direct impact on sensor resolution. Progressing from the current resolution of $\sim 6$ eV to $\sim 1$ eV will require elimination of non-design heat capacity and going to a reduced sensor size. A further goal of this study is to drive the activity per pixel to 100 Becquerel while retaining resolution.

For isotope production NuMECS will scale up from the current sub-microgram level of $^{163}$Ho to the milligram level (a factor of $10^4$). This is made possible by the very high beam currents ( 200 uA) at the Los Alamos National Laboratory(LANL) Isotope Production Facility (IPF). This can be done on a non-interference level with US medical isotope production. Scaling up has significant challenges for target design and chemical purification requiring hot cell extraction. We published recently [12] that by using a proton based method we anticipate factors of $10^4$ to $10^7$ reduced co-production of the deleterious isotope $^{166m}$Ho compared to neutron based methods. As a long term alternative, isotope production can be done at Facility for Rare Isotope Beams, FRIB ($2 \times 10^{10}$ $^{163}$Ho ions/s) implanted either directly into the sensor absorber or stopped in a pure liquid.

Scaling the experiment will benefit from the synergistic activity of multiple efforts worldwide that will further develop microwave read out techniques for a broad range of applications and allow us to use SQUID microwave multiplexing with $10^3$ channels per array, see main text. We are working on techniques to address the large data rates, digital signal processing needs and data storage questions. Engineering for measurement stability for long term runs will be a priority. This will include detailed system level Monte-Carlo simulation especially of backgrounds (potential need for anti-coincidence vetos), pile-up, cross talk and deleterious effects of $^{166m}$Ho.

The core concepts of the theory have been available since the 1980s and recent progress in self-consistent fully relativistic calculations including overlap and exchange corrections have already led to a better understanding of the recently measured O, N and M lines of the EC spectrum [23]. Future calculations will include solid-state effects introduced by the embedding matrix and final state corrections. The calculations will be cross-validated in an international collaboration of theorists from Europe and the US. The theory will be constrained by independent Penning trap measurements that will use laser ablation to minimize the mass consumption of the rare isotope and will have an anticipated resolution of the Ho to Dy mass ratio of $10^{10}$-$10^{11}$ or 15-1.5 eV [33].

The NuMECS collaboration will build a demonstrator that is based on a dilution-fridge for long term running. It will allow us to access all component technologies and put them together into a single system. The target mass sensitivity for a system that has four arrays with 1024 pixels each and an activity of 100 Becquerel per pixel operated for one year can be estimated as better then 1 eV [34–36].

This approach contrasts with technological choices of our international colleagues. ECHo has developed MMC sensors, recently producing an exciting 8eV resolution ECS spectrum of $^{163}$Ho [23], and is relying on mass separation and ion implantation at ISOLDE (CERN). HOLMES is developing a high-temperature vacuum reduction and distillation technique and is building a custom mass separator ion implanter for use with membrane-based TES sensors [34].


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