Direct Neutrino Mass Measurements with Tritium: Report to the 2022 Nuclear Science Advisory Committee

KATRIN Collaboration
Project 8 Collaboration

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In this white paper, submitted jointly by the KATRIN and Project 8 collaborations, we describe the current status of direct neutrino-mass measurements with tritium, and make recommendations for ensuring a vibrant tritium program over the next long-range-plan cycle and beyond. These recommendations include continuing operations of existing experiments, and ambitious R&D toward atomic tritium sources and the next generation of experiments.

CONTENTS

I. EXECUTIVE SUMMARY

1. Direct, kinematic measurements using tritium beta decay offer a unique opportunity to measure the neutrino mass scale in a model-independent way, providing vital information for particle theory and neutrinoless double beta decay, and a terrestrial test of the standard cosmological model. Neutrino oscillation measurements predict a lower bound for the neutrino mass scale, **establishing a definite measurement of physics beyond the original formulation of the Standard Model.** In addition, precise probes of the tritium beta spectrum offer important sensitivity to beyond-Standard-Model physics, including sterile neutrinos at eV and keV scales, exotic weak currents, Lorentz-invariance variation, and relic neutrino overdensities.

2. The KATRIN experiment leads the field in sensitivity, achieving the current best neutrino mass limit of $m_\beta < 800$ meV/c^2 at 90% C.L.; KATRIN has accumulated enough data on disk to surpass a statistical sensitivity of 500 meV/c^2. **US support for KATRIN operations and analysis efforts should continue as the collaboration pushes toward the design sensitivity of 200 meV/c^2 at 90% C.L.** Exclusive neutrino-mass operations are presently projected to conclude at the end of 2025. The next phase of KATRIN, extending to 2027, will include a dedicated search for keV-scale neutrinos with an upgraded TRISTAN detector to allow differential spectral measurements. The system will be able to toggle between physics searches that are broadly distributed over the entire tritium spectrum, and searches that are focused in the endpoint region for improved sensitivity using new means of background reduction. **Continued support for US participation in KATRIN and the Tritium Laboratory Karlsruhe will ensure the success of this phase.**

3. With the new technique of cyclotron radiation emission spectroscopy (CRES), the Project 8 experiment has made a first measurement of neutrino mass extracted from a molecular tritium spectrum. The continuous differential beta spectrum from a cm^3-scale physical detection volume is background-free. **US funding for Project 8 should continue to support R&D into resonant RF cavities to improve the available volume and scalability of CRES and into methods to create tritium atoms from molecules and then cool, transport, and trap them. The Project 8 proof-of-concept should be a pilot-scale tritium endpoint experiment with a ~ 1 m^3 atomic source and a cavity CRES detector to achieve a sensitivity target of $m_\beta \leq 400$ meV/c^2 at 90% C.L. or below.**

4. A guaranteed measurement of the neutrino-mass scale and neutrino-mass spectroscopy to resolve individual neutrino-mass states will require atomic, rather than molecular, tritium **The US should complete its investment in R&D toward a full-scale atomic-tritium experiment with a targeted mass limit of $m_\beta \leq 40$ meV/c^2.** This R&D should build on Project 8's investigations of thermal dissociation of T_2, evaporative cooling, and magnetogravitational trapping. It will be especially important to demonstrate scalable atom trapping that remains compatible with CRES.

5. Atomic-tritium R&D should leverage the operational and scientific capabilities of Tritium Laboratory Karlsruhe (TLK), where KATRIN is hosted. **Cooperation between Project 8 and KATRIN will optimize the scientific output from both collaborations in their next stages.**

II. SCIENTIFIC MOTIVATION

Experiments demonstrate that non-zero neutrino mass follows from flavor oscillation phenomena [1–8]. However, oscillation phenomena depend only on the differences of the squares of neutrino mass eigenvalues $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$; the absolute mass scale does not enter this description. The most sensitive direct way to measure neutrino mass is via high-precision spectroscopy of tritium β decay, ${}^3\mathrm{H} \to {}^3\mathrm{He}^+ + \beta^- + \bar{\nu}_e$, near its endpoint [9]. The spectral shape reveals the neutrino-mass scale m_β:

$$m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 \, m_i^2 = m_1^2 + |U_{e2}|^2 \, \Delta m_{21}^2 + |U_{e3}|^2 \, \Delta m_{31}^2 \approx m_1^2, \tag{1}$$

where U_{ei} are the matrix elements defining the coupling of the electron flavor state to each of the mass states i. Mass-squared splittings Δm_{ij}^2, measured in oscillation experiments, give a lower limit on m_β: $m_\beta > 48\,\mathrm{meV}/c^2$ if m_3 is the lightest state (inverted ordering), and $m_\beta > 8.5\,\mathrm{meV}/c^2$ if m_1 is lightest (normal ordering) (95% confidence level) [10].

Two experimental programs use the endpoint method with a tritium source: KATRIN and Project 8 (see Sec. III). The KATRIN experiment has recently employed this method to set the first sub-electronvolt limit at $m_\beta < 800\,\mathrm{meV}/c^2$ (90% C.L.) [11] on the way to its design sensitivity of $200\,\mathrm{meV}/c^2$ [12], while Project 8 is focused on R&D toward a new full-scale future neutrino mass measurement. The KATRIN measurement, together with the lower limits set by oscillation data, defines the range in which the masses must lie. If the mass is not found by KATRIN, probing the next order of magnitude in parameter space will require new spectroscopic techniques to improve the scaling relations between the statistical sensitivity, the systematic uncertainties, the size of the source, and an atomic tritium (T) source to avoid the systematic and statistical uncertainty associated with a molecular tritium (T_2) source.

Tritium β decay is not the only probe of the neutrino mass scale. Cosmological observation and models provide an indirect method for probing the neutrino mass. Hot Big Bang scenarios generally feature a cosmic neutrino background. Those neutrinos remain relativistic until a late epoch, at which time they influence the formation of large-scale structure. They also leave an imprint on the cosmic microwave background (CMB) anisotropy, suppressing structure on smaller scales in the matter power spectrum seen in baryon acoustic oscillations (BAO). The Planck satellite limit with these combined observations is $\Sigma m_i \leq 0.12\,\mathrm{eV}/c^2$ [13]. That is more restrictive than KATRIN's projected sensitivity (see Figure 1, left, for the correspondence between Σm_i and m_β). However, if cosmology turns out to require more free parameters, the limit is significantly relaxed. One compelling extension includes six parameters beyond the usual six of ΛCDM [15]. In that context the limit is $\Sigma m_i < 0.52\,\mathrm{eV}/c^2$ [16], comparable to KATRIN's projected limit. It is also the case that fixing any parameter, such as by measuring neutrino mass independently in the laboratory, would improve sensitivity to the remaining parameters that can only be extracted from cosmological data. This scenario motivates direct measurements, even in the coming age of precision cosmology, and especially if tensions like the current Hubble tension [17] persist or new ones arise.

Another potential probe is neutrinoless double beta decay, the hypothesized process that would rarely occur if (and only if) neutrinos have a Majorana nature. The US nuclear-physics community is investing significantly in neutrinoless double-beta decay searches. If observed,

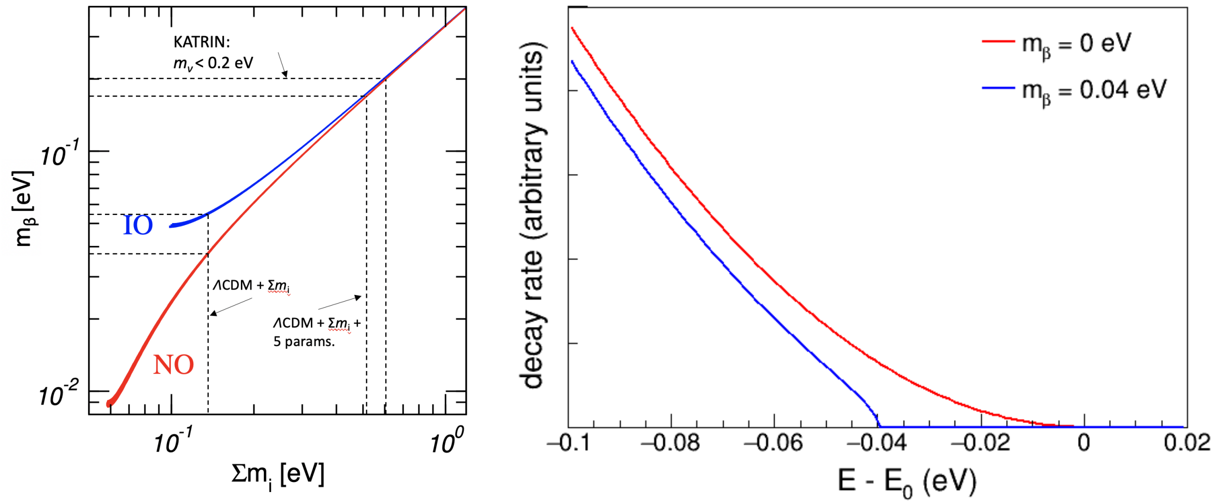

FIG. 1. Left: The relationship between the neutrino mass observable in tritium-endpoint experiments (m_β) and the observable from cosmology (Σm_i). Figure is reproduced from [14], with annotations added. Right: The differential tritium endpoint spectrum under different neutrino mass scenarios: a massless neutrino and a neutrino at the sensitivity goal of Project 8, both with the same extrapolated endpoint energy.

the rate of this process will yield information about the mass scale through the observable $\langle m_{\beta\beta}\rangle = |\sum U_{ei}^2 m_i|$ [18]. However, the extraction of this mass observable relies on knowledge of the nuclear matrix elements and on the assumption that no other lepton number violating new physics causes the decay. Here again, a direct, model-independent measurement provides crucial information.

In addition to neutrino-mass sensitivity, tritium beta decay can also probe beyond-Standard-Model physics, as discussed in recent Snowmass white papers [19, 20]. In addition to a diverse set of tests from Lorentz-invariance violation [21] to overabundance of relic neutrinos [22], these experiments can make independent, oscillation-free tests of sterile neutrino interpretations of various modern anomalies. KATRIN has already set limits on eV-scale sterile neutrinos, and its design sensitivity [23] will test large parts of the parameter space favored for sterile-neutrino interpretations of the reactor [24, 25] and recently confirmed gallium anomalies [26, 27]. A full-scale Project 8 experiment would improve further on these sensitivities [20].

This white paper outlines a plan of research – operations, analysis, and research and development (R&D) – to continue advancing our understanding of neutrinos and the standard model through the power of tritium beta decay.

III. CURRENT EXPERIMENTAL STATUS

A. MAC-E Filters: KATRIN

The KATRIN experiment started taking data in 2019. Its current neutrino-mass measurement program is projected to continue through 2025, towards the sensitivity goal of

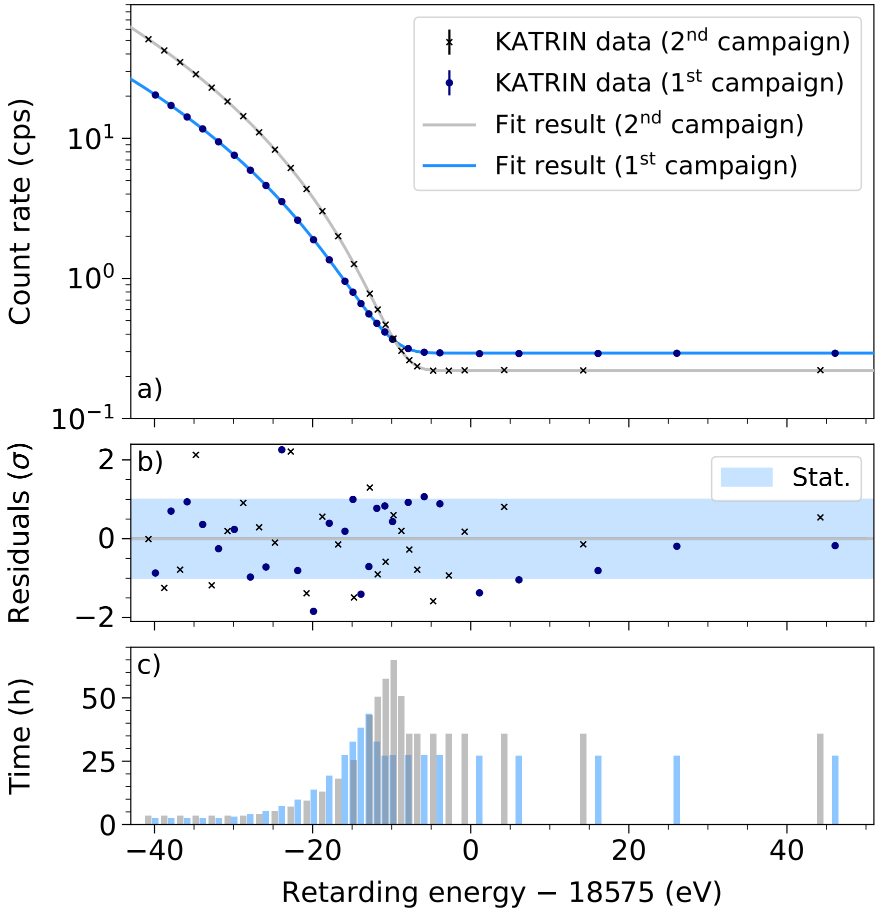

FIG. 2. Top: Measured KATRIN endpoint tritium integrated spectra from the first and second neutrino-mass measurement campaigns, along with the results of a joint fit with a common neutrino-mass-squared parameter. Center: Residuals from the two campaigns, normalized to the uncertainties. Bottom: Measurement time distribution. The "retarding energy" is the energy threshold set by the MAC-E filter. Adapted from Ref. [11].

200 meV/c^2 at 90% C.L. In KATRIN, an ultra-luminous molecular windowless gaseous tritium source (WGTS) provides an activity of up to 10^{11} Bq at a reference column density of 5×10^{17}cm^{-2}. The tritium beta decay spectrum is analyzed by a MAC-E-type spectrometer which acts as a high-pass filter. It is set to a filter width of 2.8 eV in neutrino mass measurement mode for beta electrons of 18.6 keV at the endpoint. The signal electrons passing the MAC-E filter are detected by the focal plane detector system (FPD), which supplies the pinch magnetic field to define the MAC-E filter width, provides calibration and monitoring systems, and handles the main data stream of the experiment [12]. The analysis of the first pair of measurement campaigns leads to the current best direct neutrino mass limit of $m_\beta < 800$ meV/c^2 at 90% C.L. [11] (see Figure 2). Furthermore, KATRIN has accumulated enough data on disk to surpass a statistical sensitivity of 500 meV/c^2 in the next step of analysis, and has published results for the sterile neutrino search [23]. A number of proposed modifications of the experimental setup are under investigation in order to further reduce systematic uncertainties, discriminate background events, and increase the detection efficiency by transitioning

to a differential beta-spectrum measurement (see Sec. IV A).

B. Cyclotron Radiation Emission Spectroscopy: Project 8

Over the past decade, there has been remarkable progress in demonstrating a new frequency-based technique for measuring the energy spectrum of tritium beta decay. Cyclotron radiation emission spectroscopy (CRES) uses the microwave-frequency emission from electrons in a magnetic field B to precisely measure their kinetic energy K. The radiation occurs coherently at the cyclotron frequency $f = eBc^2/(m_e c^2 + K)$.

CRES offers several distinct advantages for measuring the tritium spectrum. Unlike MAC-E filters, which measure all electrons above a chosen energy, CRES is a differential measurement, capturing the entire spectrum at once within a chosen bandwidth, giving significant statistical and systematic advantages. Furthermore, CRES is intrinsically low-background; only electrons that emit cyclotron radiation in the fiducial volume are detected. Electrons from the walls are returned immediately by the magnetic shielding and electrons generated and trapped within the volume by cosmic-ray interactions with tritium are extremely rare. The only other background source is RF thermal noise fluctuations that mimic an electron signal. Such events can be made arbitrarily rare at the expense of true event detection efficiency, limited only by signal-to-noise ratio. As the CRES signal is also frequency-based, it benefits from the high precision inherent in frequency measurements.

The technique was introduced in 2009 [28], with first verification and proof-of-concept measurement performed in 2014 using a gaseous $^{83\mathrm{m}}$Kr source of mono-energetic electrons [29]. In 2020, the Project 8 collaboration performed a first measurement of a beta decay spectrum using molecular tritium in a 10 mm diameter circular waveguide segment. The measurement confirmed many of the predicted technical advantages. An instrumental resolution of $1.7 \pm 0.2\,\mathrm{eV}$ was obtained using a high precision magnetic field configuration. For tritium running, the magnetic configuration was altered to increase detection efficiency at the expense of energy resolution. Despite the resolution broadening due to the magnetic field inhomogeneity, the measurement kept good control of the response function systematics. With a small fiducial volume of less than $5\,\mathrm{mm}^3$, Project 8 extracted its first mass limit of $m_\beta \leq 178$ eV/c^2 at 90% C.L. The tritium spectrum is shown in Fig. 3. No backgrounds were observed beyond the endpoint energy in 82 live days, consistent with the predetermined threshold whereby less than one RF-noise-induced background event was expected in the tritium data set per 100 days of run time. An upper limit on the background rate of 3×10^{-10} events/(eV s) was derived.

With the proof-of-principle established for using CRES for beta decay extraction, the next challenge is scaling the method to a larger fiducial volume. This is the focus of the present phase of the Project 8 experiment, as described in the next section.

IV. FUTURE EXPERIMENTAL EFFORTS

A. KATRIN

The KATRIN experiment will continue its measurement program until 2027, including both neutrino-mass measurements at the endpoint of the tritium spectrum and deeper spec-

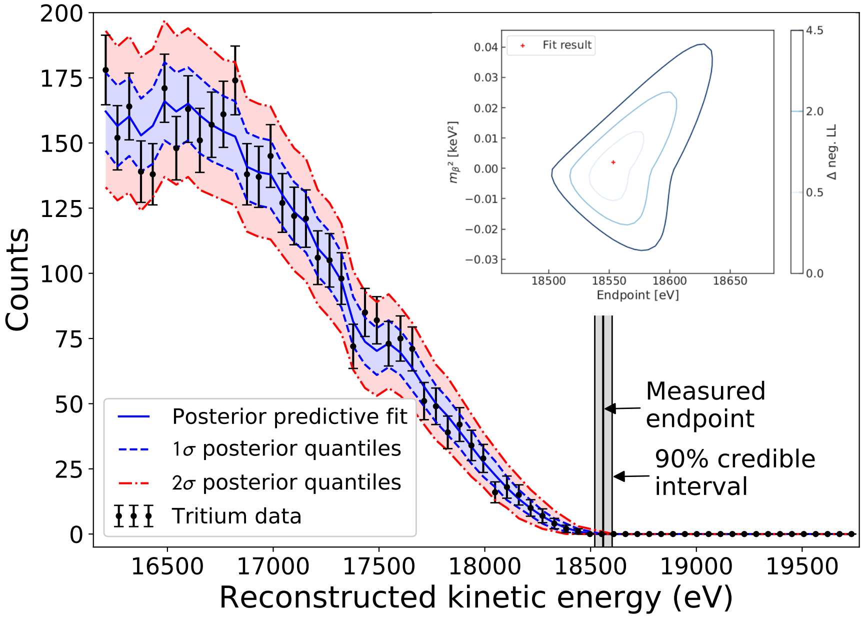

FIG. 3. The tritium spectrum measured in Phase II of Project 8.

tral searches for keV-scale sterile neutrinos. KATRIN's design sensitivity is 200 meV/c^2 at 90% C.L., improving on the previous generation of experiments by an order of magnitude. Continued support of operations and analysis is imperative for the continued success of the experiment. The collaboration is also exploring ways to further improve the experimental sensitivity by background reduction and time-of-flight measurements to enable differential detection, as described in Ref. [19].

KATRIN plans to operate in its current configuration until mid-2025, when the focal plane detector will be replaced by a multi-pixel silicon drift detector (SDD) focal plane array (TRISTAN). The SDD system features significantly improved energy resolution and rate capacity, which can be advantageous for a neutrino mass measurement. The neutrino-mass program will initially continue with the new TRISTAN detector system, after which the measurement interval will be gradually enlarged to open up the possibility for searches for physics beyond the standard model, such as keV-scale sterile neutrinos.

R&D into detectors with even higher energy resolution, allowing a differential readout of the spectrum to replace the integrated energy analysis currently performed by KATRIN's electrostatic high-pass filter, is motivated by a number of advantages. First, more statistics can be collected for a given measurement time, once a step-wise variation of the energy threshold to scan the integrated spectrum is no longer required. Moreover, a high-resolution differential measurement would allow significant background reduction. Two differential detection techniques are currently under investigation. The first is time-of-flight spectroscopy, which requires electron tagging at the entrance of the main spectrometer, using the main spectrometer on a near-endpoint voltage as a delay line and then measuring the flight-time with the focal-plane detector. As a second approach, current state-of-the-art quantum detectors such as metallic magnetic calorimeters (MMCs) may in the future provide an energy resolution in the eV range for the detection of electrons from an external source. Further development is needed to improve their magnetic-field hardness, their energy resolution, and the multiplexed readout of a large number of channels. Pathfinder experiments are underway in which MMC detectors will be characterized by external electrons from electron gun, krypton, and tritium sources.

B. Atomic Tritium

Molecular tritium has been the basis of the most sensitive neutrino mass experiments for decades because it can be provided in large amounts and the influence of molecular degrees of freedom can be calculated precisely [30]. Experiments are now approaching the point where the broadening associated with molecular vibration, rotation, and translation limits the sensitivity both statistically and systematically.

Atomic tritium is free of these effects. While technically challenging, the steps required to produce and trap atomic tritium are understood. The molecular gas can be thermally dissociated, cooled initially by contact with cold surfaces to tens of K, and cooled further to mK temperatures by evaporative cooling in a magnetic guide. Future experiments require large quantities of atomic tritium confined in a magnetic trap.

Stable isotopes of hydrogen are being used for the initial studies. Atomic tritium imposes special conditions on apparatus design, and the Tritium Laboratory Karlsruhe, with a license for 40 g of tritium, 30 years of operational experience, and a closed tritium cycle with isotopic purification, is a suitable location for R&D. Coupling an atomic tritium beam to the existing KATRIN infrastructure, eventually with a differential detector, would help in studying and identifying systematic effects related to a source of this type.

As further detailed below, Project 8 plans to perform CRES measurements on atomic tritium maintained in a multi-polar magnetic trap made from permanent magnets (a Halbach array) or superconductors (a Ioffe-Pritchard trap) [31]. An external solenoid will provide a uniform background magnetic field for CRES in the central region. The trap loss mechanisms have been identified. In order of decreasing importance, they are: dipolar interactions that flip the atom spin, evaporation over the magnetic wall, loss through the injection port, radioactive heating, heat leaks from ^{3}He and molecular T_2, volume recombination, and Majorana spin flips. Current estimates of the losses from such a trap indicate that a net efficiency of 1×10^{-4} from a molecular supply of 1×10^{19} molecules/s is sufficient. The densities are low enough that volume recombination is insignificant, and trap lifetimes of order 1000 s can be obtained. A relatively low magnetic field of <50 mT is required to minimize dipolar losses [32]. The requirements for magnetic trapping of electrons and of atoms are different, and to decouple them Project 8 will use a magnetogravitational atom trap with a resonant cavity ∼10 m in height. That, in turn, sets the temperature for atoms at ∼1 mK.

The elements of an intense source of atomic tritium have been identified. It is important to begin experimental R&D efforts of each stage as soon as possible to assure readiness for the neutrino mass program.

C. Project 8

The next steps for Project 8 are to increase dramatically the size of the tritium volume and to develop a source of atomic tritium. The statistical precision depends on the total number of atoms emitting detectable electrons. It is also necessary for both statistical and systematic reasons to obtain high resolution, comparable to the neutrino mass scale that is to be measured.

While the first tritium experiment was carried out in a 1 T field, much lower fields will be needed in the future, driven both by the scaling of resonant cavity volumes as the cube of the wavelength and by the reduced dipolar losses in a trapped atomic tritium source. In the period of the forthcoming Long Range Plan, three demonstrator experiments are planned:

- **Cavity CRES Apparatus (CCA):** The CCA will demonstrate that CRES works in a resonant cavity environment using $^{83\mathrm{m}}$Kr and Mott-scattered electrons from a high-resolution electron gun as sources. This small (few cm^3) cavity will operate in an existing magnet at 0.94 T ($f = 26$ GHz), reusing signal processing, DAQ, and analysis from prior waveguide experiments.

- **Atomic Tritium Demonstrator (ATD):** The ATD will show that tritium atoms can be trapped at the purity, density, and temperature required by Project 8.

- **Pilot-scale Tritium-Endpoint Experiment:** A much larger (several m^3) cavity-based experiment operable with both molecular and atomic tritium will be capable of sub-electronvolt m_β sensitivity. This will advance the technique of cavity CRES, demonstrating the feasibility of operating at the much larger size scale required for sensitivity beyond the KATRIN era. This experiment will operate at lower field: approximately 0.04 T, corresponding to 1 GHz cyclotron signals. In its final form with a source of cold tritium atoms and a large atom trap, the projected sensitivity is $\leq$400 meV, making this a world-class neutrino mass experiment in its own right.

These three demonstrators will establish the scalability of the CRES technique and prepare the necessary infrastructure for a full-scale atomic tritium neutrino mass experiment.

V. OUTLOOK

KATRIN will continue acquiring high-quality tritium data while pursuing active R&D for an upgraded detector, for improved background rejection, and for future possibilities including atomic tritium and differential spectral measurement. A rough timeline is below.

2022-2025: KATRIN continues neutrino-mass data taking alongside work on potential upgrades to reduce statistical and systematic uncertainties. Atomic tritium R&D begins at TLK.
2025: Primary KATRIN detector is replaced with SDD array (TRISTAN). Spectral measurements continue in endpoint region (including data for both neutrino-mass and BSM searches) and beyond, for keV-scale sterile-neutrino searches.
2027: KATRIN completes measurement phase planned in current HGF funding period, including neutrino-mass and keV-sterile searches. Analyses of data are continued.
2027+: Continued R&D efforts in support of the global tritium program. Data analysis is completed.

Project 8 will follow an R&D path along which the concepts of a full-scale CRES experiment will be developed and tested, at first individually and then in concert. The timeline below is technically limited and approximate.

2022-2024: Construct and test a high-resolution electron gun and a 26 GHz cavity in a 1 T field to study electron signals from both Mott scattering of electrons on He and $^{83\mathrm{m}}$Kr decay. This will be the first exploration of resonant cavities for CRES. Build lower-frequency cavities at about 1 GHz for electromagnetic studies.

2022-2025: Develop and test atomic hydrogen and deuterium sources and an evaporative-cooling beamline. Develop and test a medium-scale Halbach array and/or Ioffe-Pritchard multipole for demonstrating magnetic trapping.

2024-2026: Source a tritium-handling system and liquid helium plant from commercial suppliers, with associated CRES design effort.

2025-2027: Develop and test an atomic tritium source and evaporative-cooling beamline.

2022-2029: Develop and construct a pilot-scale (several cubic meters) cavity-based experiment, including all magnets, for CRES measurements with both molecular and atomic tritium. This system, potentially reaching about 1/30 the rate capability of the final Phase IV apparatus, represents a frontier neutrino mass experiment in its own right with sensitivity of 400 meV or below.

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[1] Y. Fukuda, T. Hayakawa, E. Ichihara, K. Inoue, K. Ishihara, H. Ishino, Y. Itow, T. Kajita, J. Kameda, S. Kasuga, et al. (Super-Kamiokande), Phys. Rev. Lett. **81**, 1562 (1998), URL http://link.aps.org/doi/10.1103/PhysRevLett.81.1562.

[2] Q. R. Ahmad, R. C. Allen, T. C. Andersen, J. D. Anglin, G. Bühler, J. C. Barton, E. W. Beier, M. Bercovitch, J. Bigu, S. Biller, et al. (SNO Collaboration), Phys. Rev. Lett. **87**, 071301 (2001), URL http://link.aps.org/doi/10.1103/PhysRevLett.87.071301.

[3] Q. R. Ahmad, R. C. Allen, T. C. Andersen, J. D.Anglin, J. C. Barton, E. W. Beier, M. Bercovitch, J. Bigu, S. D. Biller, R. A. Black, et al. (SNO Collaboration), Phys. Rev. Lett. **89**, 011301 (2002), URL http://link.aps.org/doi/10.1103/PhysRevLett.89.011301.

[4] K. Eguchi, S. Enomoto, K. Furuno, J. Goldman, H. Hanada, H. Ikeda, K. Ikeda, K. Inoue, K. Ishihara, W. Itoh, et al. (KamLAND Collaboration), Phys. Rev. Lett. **90**, 021802 (2003), URL http://link.aps.org/doi/10.1103/PhysRevLett.90.021802.

[5] B. Aharmim, S. N. Ahmed, J. F. Amsbaugh, A. E. Anthony, J. Banar, N. Barros, E. W. Beier, A. Bellerive, B. Beltran, M. Bergevin, et al. (SNO), Phys. Rev. Lett. **101**, 111301 (2008), 0806.0989.

[6] K. Abe, N. Abgrall, Y. Ajima, H. Aihara, J. B. Albert, C. Andreopoulos, B. Andrieu, S. Aoki, O. Araoka, J. Argyriades, et al. (T2K Collaboration), Phys. Rev. Lett. **107**, 041801 (2011), URL http://link.aps.org/doi/10.1103/PhysRevLett.107.041801.

[7] F. P. An, J. Z. Bai, A. B. Balantekin, H. R. Band, D. Beavis, W. Beriguete, M. Bishai, S. Blyth, K. Boddy, R. L. Brown, et al., Phys. Rev. Lett. **108**, 171803 (2012), URL http://link.aps.org/doi/10.1103/PhysRevLett.108.171803.

[8] J. K. Ahn, S. Chebotaryov, J. H. Choi, S. Choi, W. Choi, Y. Choi, H. I. Jang, J. S. Jang, E. J. Jeon, I. S. Jeong, et al. (RENO Collaboration), Phys. Rev. Lett. **108**, 191802 (2012), URL http://link.aps.org/doi/10.1103/PhysRevLett.108.191802.

[9] J. A. Formaggio, A. L. C. de Gouvêa, and R. G. H. Robertson, Physics Reports **914**, 1 (2021), URL https://www.sciencedirect.com/science/article/pii/S0370157321000636.

[10] P. A. Zyla, R. M. Barnett, J. Beringer, O. Dahl, D. A. Dwyer, D. E. Groom, C. J. Lin, K. S. Lugovsky, E. Pianori, D. J. Robinson, et al., Progress of Theoretical and Experimental Physics **2020** (2020), ISSN 2050-3911, 083C01, https://academic.oup.com/ptep/article-pdf/2020/8/083C01/33653179/ptaa104.pdf, URL https://doi.org/10.1093/ptep/ptaa104.

[11] M. Aker et al. (KATRIN), Nature Phys. **18**, 160 (2022), 2105.08533.

[12] M. Aker et al. (KATRIN), Journal of Instrumentation **16**, T08015 (2021), URL https://doi.org/10.1088/1748-0221/16/08/t08015.

[13] N. Aghanim et al. (Planck), Astron. Astrophys. **641**, A6 (2020), 1807.06209.

[14] I. Esteban, M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, and T. Schwetz, Journal of High Energy Physics **2019**, 106 (2019), URL https://doi.org/10.1007/JHEP01(2019)106.

[15] E. Di Valentino, A. Melchiorri, and J. Silk, Phys. Rev. D **92**, 121302 (2015), URL https://link.aps.org/doi/10.1103/PhysRevD.92.121302.

[16] M. Tanabashi et al. (Particle Data Group), Phys. Rev. **D98**, 030001 (2018).

[17] E. Di Valentino, A. Melchiorri, and J. Silk, Nature Astronomy **4**, 196 (2020), URL https://doi.org/10.1038/s41550-019-0906-9.

[18] M. J. Dolinski, A. W. Poon, and W. Rodejohann, Annu. Rev. Nucl. Part. Sci. **69**, 219 (2019), https://doi.org/10.1146/annurev-nucl-101918-023407, URL `https://doi.org/10.1146/annurev-nucl-101918-023407`.

[19] M. Aker et al. (KATRIN), J. Phys. G **49**, 100501 (2022), 2203.08059.

[20] A. A. Esfahani et al. (Project 8), in *2022 Snowmass Summer Study* (2022), 2203.07349.

[21] M. Aker et al. (KATRIN) (2022), 2207.06326.

[22] M. Aker et al. (KATRIN), Phys. Rev. Lett. **129**, 011806 (2022), 2202.04587.

[23] M. Aker, D. Batzler, A. Beglarian, J. Behrens, A. Berlev, U. Besserer, B. Bieringer, F. Block, S. Bobien, B. Bornschein, et al., Physical Review D **105** (2022), URL `https://doi.org/10.1103%2Fphysrevd.105.072004`.

[24] T. A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot, T. Lasserre, J. Martino, G. Mention, et al., Phys. Rev. C **83**, 054615 (2011), URL `http://link.aps.org/doi/10.1103/PhysRevC.83.054615`.

[25] G. Mention, M. Fechner, T. Lasserre, T. A. Mueller, D. Lhuillier, M. Cribier, and A. Letourneau, Phys. Rev. D **83**, 073006 (2011), URL `http://link.aps.org/doi/10.1103/PhysRevD.83.073006`.

[26] V. V. Barinov, S. N. Danshin, V. N. Gavrin, V. V. Gorbachev, D. S. Gorbunov, T. V. Ibragimova, Y. P. Kozlova, L. V. Kravchuk, V. V. Kuzminov, B. K. Lubsandorzhiev, et al., Phys. Rev. C **105**, 065502 (2022), URL `https://link.aps.org/doi/10.1103/PhysRevC.105.065502`.

[27] V. V. Barinov, B. T. Cleveland, S. N. Danshin, H. Ejiri, S. R. Elliott, D. Frekers, V. N. Gavrin, V. V. Gorbachev, D. S. Gorbunov, W. C. Haxton, et al., Phys. Rev. Lett. **128**, 232501 (2022), URL `https://link.aps.org/doi/10.1103/PhysRevLett.128.232501`.

[28] B. Monreal and J. Formaggio, Phys. Rev. **D80**, 051301 (2009).

[29] D. M. Asner, R. F. Bradley, L. de Viveiros, P. J. Doe, J. L. Fernandes, M. Fertl, E. C. Finn, J. A. Formaggio, D. Furse, A. M. Jones, et al. (Project 8 Collaboration), Phys. Rev. Lett. **114**, 162501 (2015), URL `http://link.aps.org/doi/10.1103/PhysRevLett.114.162501`.

[30] A. Saenz, S. Jonsell, and P. Froelich, Phys. Rev. Lett. **84**, 242 (2000), URL `http://link.aps.org/doi/10.1103/PhysRevLett.84.242`.

[31] J. Ahokas et al., Rev. Sci. Instrum. **93**, 023201 (2022), 2108.09123.

[32] A. Lagendijk, I. F. Silvera, and B. J. Verhaar, Phys. Rev. B **33**, 626 (1986), URL `https://link.aps.org/doi/10.1103/PhysRevB.33.626`.