Final scientific and technical report: New experiments to measure the neutrino mass scale

University of California, Santa Barbara
Department of Physics
Santa Barbara, CA 93106
PI: Benjamin Monreal
Associate Professor of Physics
5123 Broida Hall, University of California, Santa Barbara
Santa Barbara, CA 93106
phone: 805-893-3440
email: bmonreal@physics.ucsb.edu
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1 Executive summary

In this work, we made material progress towards future measurements of the mass of the neutrino. The neutrino is a fundamental particle, first observed in the 1950s and subjected to particularly intense study over the past 20 years. It is now known to have some, non-zero mass, but we are in an unusual situation of knowing the mass exists but not knowing what value it takes. The mass may be determined by precise measurements of certain radioactive decay distributions, particularly the beta decay of tritium. The KATRIN experiment is an international project which is nearing the beginning of a tritium measurement campaign using a large electrostatic spectrumeter. This research included participation in KATRIN, including construction and delivery of a key calibration subsystem, the "Rear Section". To obtain sensitivity beyond KATRIN's, new techniques are required; this work included R&D on a new technique we call CRES (Cyclotron Resonance Electron Spectroscopy) which has promise to enable even-more-sensitive tritium decay measurements.

We successfully carried out CRES spectroscopy in a model system in 2014, making an important step towards the design of a next-generation tritium experiment with new neutrino mass measurement abilities.

2 New experiments to measure the neutrino mass scale

The research proposed in this grant encompassed design, modeling, and experimental activity connected with direct measurements of the neutrino mass scale, particularly by (a) developing the Project 8 concept for cyclotron radiation electron spectroscopy and (b) participating in the KATRIN experiment, particularly development of the KATRIN "rear section", a suite of calibration equipment attached to the KATRIN tritium source.

During the funding period, the PI helped lead an international collaboration which demonstrated the first "cyclotron resonance electron spectroscopy", or CRES, detecting single ^{83m}Kr conversion electrons in a small magnetic trap in a waveguide. The first detections took place in 2014 and were published and widely reported in 2015, and were featured as a "science highlight" by the DOE Office of Nuclear Physics. As originally proposed, successful demonstration of CRES in ^{83m}Kr opens the door to a CRES-based measurement of tritium decay,

2.1 KATRIN

We proposed to participate in KATRIN via design and construction of the "Rear Section", which includes both a high-precision electron beam system ("E-gun") and a special plasma electrode (the "Rear Wall") both of which provide calibration and stability assurance to the complex, highly dynamic tritium gas pipe which is the source of KATRIN's electrons. Since the Rear Section is closely interfaced with a very strong gaseous radioactive source, it design had to obey tritium-containment design standards.

In the early phase of this project (2010–2011) our major focus was the conceptual design of the E-gun, largely using KATRIN's own electromagnetic software toolkits to choose electrode and magnet configurations capable of generating the types of beams we needed. This was closely integrated with KATRIN simulation/physics analyses which helped set the beam quality requirements. Our major accomplishment on this front was demonstration that such an electron gun could generate beams with narrow, selectable pitch-angular distributions, and that a self-calibration sequence we invented could be used to map out the performace of the system as-built. (This technique was adopted successfully by other KATRIN electron guns, including the “Munster e-gun” used for flagship KATRIN spectrometer calibration.) We moved from simulation to engineering design (2011–2013) including several rounds of engineering design reports submitted to our Karlsruhe collaborators; in addition to reaching physics performance and reliability goals, we had to ensure compliance with tritium safety regulations. Towards the end of the grant period (2013–2015) we began construction work. The E-gun included electromagnetic components, UV optics, and vacuum and 2nd-containment components. We chose to build the electromagnetic components (electrodes, magnets, and some power supplies) at UCSB, to be integrated with a vacuum and containment system built at KIT. We did a full E-gun assembly in a mockup vacuum system at UCSB and conducted a detailed beam calibration campaign here before shipping the apparatus to Germany in 2015. Custom optics were built at UCSB for the local beam campaign, but a commercial monochromator system was later selected and integrated for KATRIN.

The physics requirements for the “Rear Wall” were studied closely in the early period (2010–2012) and turned out to require a lot of basic materials characterization. During this period, we did a large number of R&D cycles studying the crystallographic and electrostatic properties of gold films plated in various ways, eventually concluding (contrary to the original vision) that a monocrystalline wall was not obtainable in the size required, but that the polycrystalline textured walls we were obtaining had the desired electrostatics. This made it possible for our KIT collaborators to create and characterize the gold/steel wall which is being integrated into KATRIN now. We pursued an original idea we had for producing a “multilayer” wall, basically serving as a Faraday cup able to measure DC currents. We obtained an old electron microscope and converted it into a beam/wall interaction test stand. Although we successfully demonstrated Faraday-cup behavior in small samples, the method did not scale well to large walls and was not selected for KATRIN integration. The beam/wall interaction test stand did, however, produce novel electron/gold inelastic scattering spectra which may prove important for KATRIN sterile neutrino searches. This became the topic of a Ph.D. thesis.

KATRIN as a whole is now (late 2016) fully assembled, under vacuum, extensively calibrated, and undergoing beam alignment checks in preparation for 2017 tritium operations. Early operations are expected

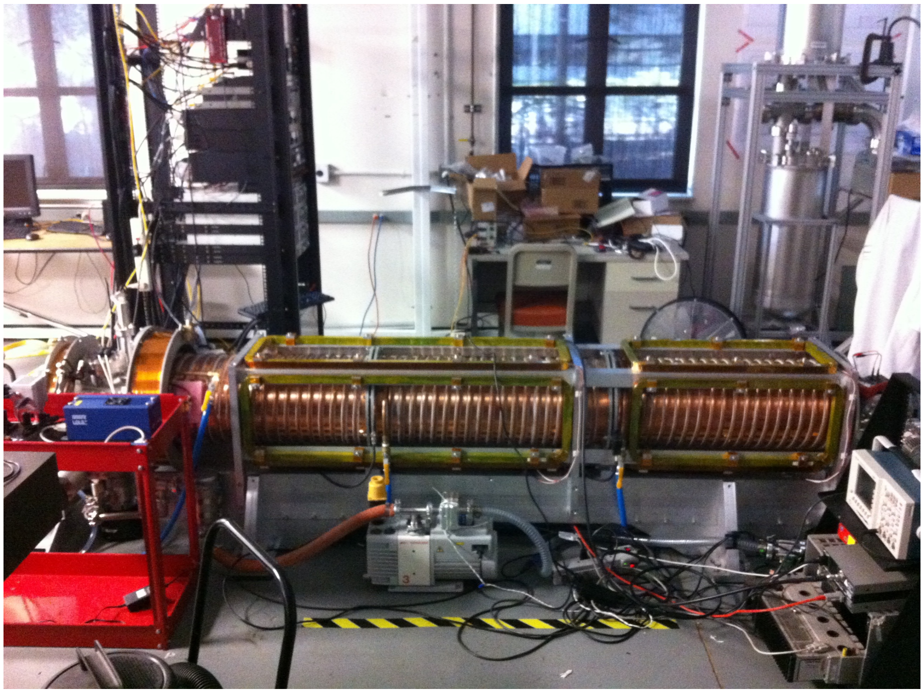

Figure 1: The KATRIN electron gun assembled and under test at UCSB. Visible components include a long water-cooled solenoid magnet, boxed in by rectangular steering coils. Electrons are launched from a mechanically-movable photocathode housed within the larger magnet coils on the left.

to yield the first new direct neutrino mass limits since 2005.

2.2 Project 8

In 2009, the Project 8 concept existed only in sketch form—that tritium beta decay electrons emit cyclotron radiation, which may be detectable, and which carries frequency information which in principle allows a precise energy measurement. The details—how to detect the radiation, trap the electrons, understand the spectrum, etc.—required elucidation, in a complex environment with a large number of interrelated constraints. We formed the "Project 8 collaboration" to move this forward. Early work at UCSB was, to a large extent, pure electromagnetic theory. In particular, in order to design the apparatus we needed a good understanding of trapped-electron coupling to complex electromagnetic structures like waveguides and cavities; a fairly complete theory, obtained in 2010 at UCSB, showed that good signals could be expected from elec-

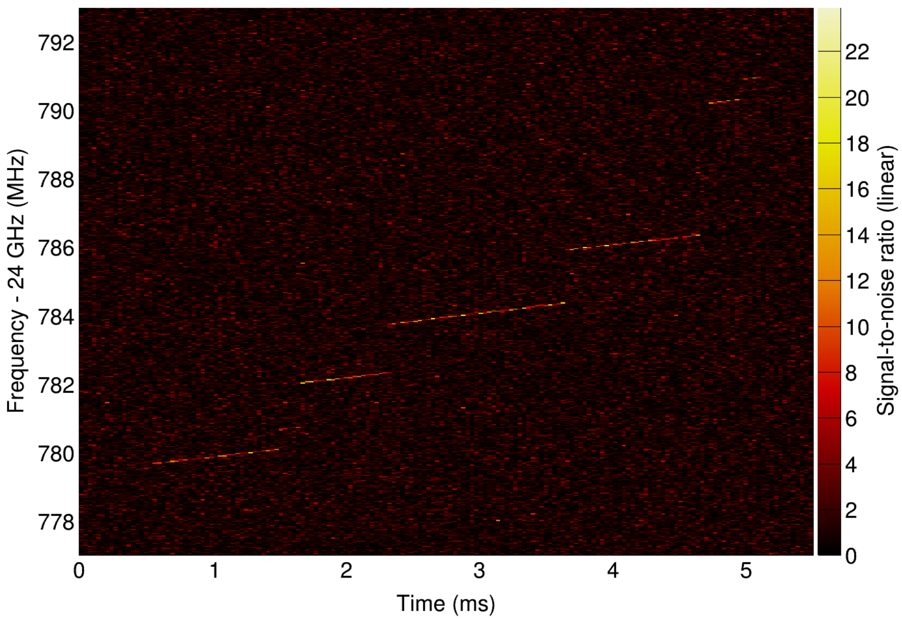

Figure 2: Frequency vs. time spectrogram showing a single electron emitting cyclotron radiation over several milliseconds.

trons trapped in a waveguide. This was the basis of development of the main Project 8 apparatus. Early work began with a refurbishment of a magnet at the University of Washington, which proved unreliable and was replaced with a surplus NMR magnet obtained by and shipped from UCSB. An extensive collaborative effort followed, leading to CRES signal detection in late 2013 and published in 2014. UCSB's contributions included hardware (amplifiers) and extensive hands-on contributions to slow control, data acquisition, data handling, and data analysis. The CRES apparatus has been in a continuous cycle of upgrades, operations, and calibrations since the discovery.

The early success of CRES has made it possible to move materially closer to the design of a large CRES-based tritium endpoint experiment. This design effort is now underway and widely recognized in the neutrino community. At UCSB, we have engaged closely with engineering/cost studies of a low-magnetic-field option; theoretical studies of a "maser" version of the experiment; and efforts to map out possible sources of systematic error.

3 Publications

Refereed journal articles

[1] M Arenz et al. Commissioning of the vacuum system of the KATRIN main spectrometer. *Journal of Instrumentation*, 11(4):04011, 2016.

[2] R. Adhikari et al. A White Paper on keV Sterile Neutrino Dark Matter. *Accepted by JCAP*, 2016, 1602.04816.

[3] B. Monreal. Quick study: Single-electron cyclotron radiation. *Physics Today*, 69(1):70, 2016. Invited article.

[4] 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, J. N. Kofron, B. H. LaRoque, M. Leber, E. L. McBride, M. L. Miller, P. Mohanmurthy, B. Monreal, N. S. Oblath, R. G. H. Robertson, L. J Rosenberg, G. Rybka, D. Rysewyk, M. G. Sternberg, J. R. Tedeschi, T. Thümmler, B. A. VanDevender, and N. L. Woods. Single-electron detection and spectroscopy via relativistic cyclotron radiation. *Phys. Rev. Lett.*, 114:162501, Apr 2015. Editor's Suggestion, featured in *Physics*.

[5] C. Adams et al. The Intermediate Neutrino Program. In *Workshop on the Intermediate Neutrino Program (WINP 2015) Upton, NY, USA, February 4-6, 2015*, 2015, 1503.06637.

[6] Benjamin Monreal. The Project 8 radiofrequency tritium neutrino experiment. *Physics Procedia*, 61(0):274 – 277, 2015. 13th International Conference on Topics in Astroparticle and Underground Physics (TAUP) 2013.

[7] L. Accardo et al. High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the International Space Station. *Phys.Rev.Lett.*, 113:121101, 2014.

[8] A. de Gouvea et al. Working Group Report: Neutrinos. In *Community Summer Study 2013: Snowmass on the Mississippi (CSS2013) Minneapolis, MN, USA, July 29-August 6, 2013*, 2013, 1310.4340.

[9] P. J. Doe et al. Project 8: Determining neutrino mass from tritium beta decay using a frequency-based method. In *Community Summer Study 2013: Snowmass on the Mississippi (CSS2013) Minneapolis, MN, USA, July 29-August 6, 2013*, 2013, 1309.7093.

[10] M. Babutzka, M. Bahr, J. Bonn, B. Bornschein, A. Dieter, et al. Monitoring of the operating parameters of the KATRIN Windowless Gaseous Tritium Source. *New J.Phys.*, 14:103046, 2012, 1205.5421.

[11] Project 8 Collaboration. Project 8: Update on a radiofrequency tritium spectrometer. *AIP Conference Proceedings*, 1441(1):441–443, 4 2012.

Confence presentations

[1] New results from Project 8 (invited). In *APS April Meeting*, Baltimore, 2015.

[2] The Project 8 neutrino mass experiment (invited). In *Topics in Astroparticle and Underground Physics*, Asilomar, 2013.

[3] Neutrino mass searches (invited). In *INPAC-MRPI annual meeting*, Asilomar, 2013.

[4] Katrin. In *INPAC-MRPI annual meeting*, Asilomar, 2011.

[5] Project 8. In *The Future of Neutrino Mass Measurements: Terrestrial, Astrophysical, and Cosmological Measurements in the Next Decade*, Seattle, 2010.

[6] Project 8. In *Advances in Neutrino Technology*, Santa Fe, 2010.