Project 8: Determining neutrino mass from tritium beta decay using a frequency-based method

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I. EXCECUTIVE SUMMARY

Neutrino mass remains one of the most important open questions in physics. Direct, laboratory determinations based on the precise measurement of the beta spectrum of tritium have set an upper limit of 2 eV/c^2 on the average mass of the three eigenstates. A very large scale tritium experiment, KATRIN, is nearing completion that will have a sensitivity of 0.2 eV/c^2, an order of magnitude below the current limit. Neutrino oscillations establish that neutrinos do have mass, and set a lower limit on the average mass of 0.02 eV/c^2. Cosmology is sensitive to masses in this range because neutrinos undergo a transition from radiation-like to matter-like as the universe expands and cools, and so affect the formation of large-scale structure. Because cosmological models depend on the properties of ingredients about which little is known, a laboratory-based measurement of neutrino mass is highly desirable and would serve to constrain better the unknown aspects of cosmology .

A new technique for beta spectrometry has recently been developed in nuclear physics, Cyclotron Radiation Emission Spectroscopy (CRES). It offers the prospect of a different method for measuring neutrino mass, one that could provide a result using molecular tritium with a sensitivity comparable to KATRIN's but with quite different systematics. The advantages of CRES include the fact that the measurement is frequency-based, and that the source is transparent to the emitted radiation. Beta electrons themselves need not be extracted from the source for measurement. The method moreover lends itself to consideration of an atomic tritium experiment, which would eliminate the final-state broadening caused by the internal motions of the tritium molecule T_2. With such a source it would be possible in principle to extend the measurement sensitivity all the way down to the inverted hierarchy scale, about 0.05 eV.

A direct measurement in the sub-eV mass range is important not only for cosmology and the structure of the new Standard Model, but would also illuminate a key unknown in the search for neutrinoless double beta decay.

II. SCIENTIFIC MOTIVATION

An astonishing number of discoveries have taken place over the last decade that have led to a revolution in our understanding of neutrinos. Whereas just fifteen years ago it was commonly accepted that neutrinos were massless particles, a number of key experiments have shown that concept was incorrect. Measurements accumulated from solar [1–6], atmospheric [7], and reactor [8, 9] neutrinos have shown conclusively that neutrinos change flavor and, as a consequence, have a very small but nonzero mass. However, because neutrino oscillation experiments are only sensitive to mass differences, they cannot determine the overall scale of neutrino masses. Nevertheless, results from oscillation experiments do provide a lower bound on the absolute neutrino mass scale. Our current knowledge of the neutrino mass scale and the neutrino hierarchy is a powerful reminder that our standard model of nuclear and particle physics remains incomplete.

Direct measurements of the neutrino mass can provide direction as to how to extend that model, with implications for nuclear physics, particle physics, astrophysics, and cosmology (See Table I). There are many theories beyond the Standard Model that explore the origins of neutrino masses and mixing. In these theories, which often work within the framework of supersymmetry, neutrinos naturally acquire small but non-zero masses. Several models use the so-called see-saw effect to generate neutrino masses. Other classes of theories are based on completely different possible origins of neutrino masses, such as radiative corrections arising from an extended Higgs sector. As neutrino masses are much smaller than the masses of the other fermions, the knowledge of the absolute values of neutrino masses is crucial for our understanding of the fermion masses in general. Recently it has been pointed out that the absolute mass scale of neutrinos may be even more significant and straightforward for the fundamental theory of fermion masses than the determination of the neutrino mixing angles and CP-violating phases [10]. It will likely be the absolute mass scale of neutrinos which will determine the scale of new physics.

Neutrinos and their properties also play an important role in astrophysics and cosmology. In cosmology, relic neutrinos may constitute an important fraction of the hot dark matter influencing the evolution of large scale structures. The imprint of neutrino mass on structure evolution is quite distinct from other dark matter candidates such as supersymmetric particles. Cosmological models of structure formation strongly depend on the relative amounts of cold and hot dark matter in the universe. As a result, the determination of the neutrino contribution Ω_ν to the total dark matter content Ω_m of the universe is important for our understanding of structure formation [11]. This link between neutrino physics and cosmology is a strong motivation for the next-generation terrestrial neutrino mass experiments.

TABLE I: Impact of electron-weighted neutrino mass sensitivity level as obtained from beta decay measurements on nuclear physics and cosmology.

Neutrino Mass Sensitivity	Scale	Possible Experiments	Impact
$m_\nu > 2$ eV (current sensitivity)	eV	Mainz, Troitsk, Project 8 (Phase II)	Neutrinos ruled out as primary dark matter
$m_\nu > 0.2$ eV	Degeneracy	KATRIN Project 8 (Phase III)	Cosmology, $0\nu\beta\beta$ reach
$m_\nu > 0.05$ eV	Inverted Hierarchy	Project 8 (Phase IV)	Resolve hierarchy if null result
$m_\nu > 0.01$ eV	Normal Hierarchy	Unknown	Oscillation limit, possible relic neutrino sensitivity

Beyond the quasi-degenerate scale, there is also great scientific incentive to push to the inverted hierarchy scale (that is, 50 meV). Should the neutrino mass ordering be inverted, then one expects a positive signal. Therefore, a null result would have significant implications, establishing the hierarchy as normal. Such knowledge would be quite complementary to that achieved by neutrino-less double beta decay and the neutrino oscillation long-baseline program.

III. TECHNIQUE DESCRIPTION

Project 8 is based on a new idea for electron spectroscopy described by Monreal and Formaggio [12]. Electrons spiraling in a magnetic field emit cyclotron radiation that can be detected. Because of the relativistic mass increase, the frequency is a measure of the electron total energy. Since a gaseous tritium source is transparent to the cyclotron radiation, this approach can evade the limit set by source thickness. The cyclotron angular frequency is

$$f_\gamma \equiv \frac{\omega_c}{2\pi\gamma} = \frac{eB}{2\pi\gamma m_e}, \tag{1}$$

where $e\,(m_e)$ is the electron charge (mass), c is the speed of light in vacuum, and γ is the Lorentz factor. The non-relativistic frequency f_c is $2.799\,249\,110(6) \times 10^{10}$ Hz at 1 T [13]. The orbiting electron emits coherent electromagnetic radiation with a power spectrum that is strongly peaked at f_γ. For 18.6-keV electrons, $\gamma = 1.0364$, for which in a 1 Tesla field the measurable cyclotron frequency is 27.009 GHz. A measurement of the energy to a precision of 1 eV implies a frequency measurement with a precision of 2×10^{-6}. That in turn implies an observation time of ≈ 2.7 μs, setting a lower limit on the mean time for an interaction with the background gas.

The power radiated is significant, scaling as B^2: indeed, energy losses due to radiation set a limit on the usable magnetic field. At 1 T, the power is of order 1 fW, detectable with modern radio-astronomy electronics. Thus the basic concept of a tritium beta-decay experiment is relatively simple: a uniform magnetic field, a radio receiver, and low-pressure tritium gas. In a realistic apparatus many additional considerations enter. The path length for an 18.6 keV electron traveling for 2.7 μs is 200 m, exceeding the size of a practical uniform-field magnet. A trap configuration is therefore necessary. The maximum permissible gas density is set by the interaction cross section of about 3×10^{-18}cm^2 [14] and the desired energy resolution. The amount of tritium to reach a certain mass sensitivity and the efficiency together then determine the volume that must be instrumented.

Scaling up the volume improves the statistical accuracy and also allows longer times between interactions with gas molecules and therefore better resolution. However, there are both instrumental and fundamental limits to the resolution. The uncertainties in those contributions translate into an uncertainty in the neutrino mass, setting a limit on the sensitivity no matter how large the volume. Extending the mass reach requires an increase in the instrumented volume that scales at least as fast as the inverse cube of the mass, which will be very demanding in magnet and RF design below 1 eV. Daunting as that prospect is, it is at least possible to consider an attack on the previously inaccessible mass range below 0.2 eV. A fundamental limit to any experiment using T_2 is the broadening caused by the molecular states in the THe^+ ground state populated in the decay. The distribution can be calculated accurately [15] but it nevertheless represents an effective irreducible linewidth of 1 eV FWHM. Atomic tritium eliminates this contribution and is under consideration.

A. Projected Neutrino Mass Sensitivity

For an electron-flavor-weighted neutrino mass m_ν, where $m_\nu^2 = \sum_i |U_{ei}|^2 m_{\nu,i}^2$, the tritium beta spectrum near the endpoint can be written in a simplified form,

$$\frac{dN}{dE_e} = 3rt(E_0 - E_e)\left[(E_0 - E_e)^2 - m_\nu^2\right]^{\frac{1}{2}} \tag{2}$$

where r is the rate in the last eV of the spectrum in the absence of mass, t is the running time and E_0 is the endpoint energy. The neutrino mass can be determined from a single measurement of the number of events in an interval ΔE from the endpoint energy, as long as other parameters, namely the rate, time, endpoint energy, and background, are well enough known. This is an idealization but not unrealistic for an experiment like Project 8 where very high statistics data on background and the spectrum below the endpoint are automatically taken "for free" because all events are recorded as they occur (KATRIN takes data point-by-point.). One can do still better statistically by gaining more information about the distribution of events within the window E, but this ansatz provides a robust statistical baseline for estimating the precision that can be obtained. It is not assumed that the endpoint energy is known in an absolute sense; it need only be determined relative to the analysis window.

The total number of signal events N_s in this analysis window is obtained by integrating Eq. 2,

$$N_s = rt(\Delta E)^3\left[1 - \frac{3}{2}\frac{m_\nu^2}{(\Delta E)^2}\right]. \tag{3}$$

If there is an additional background b that is energy-independent and proportional to the width ΔE of the analysis window, the total number of events is

$$N_{\rm tot} = rt(\Delta E)^3\left[1 - \frac{3}{2}\frac{m_\nu^2}{(\Delta E)^2}\right] + bt\Delta E. \tag{4}$$

The statistical uncertainty $\sigma^2_{m^2_\nu}$ is thus related to the variance in the total number of events:

$$\begin{aligned}
\sigma_N^2 &= (\frac{\partial N_{\rm tot}}{\partial m_\nu^2})^2 \sigma^2_{m_\nu^2} \\
\frac{\partial N_{\rm tot}}{\partial m_\nu^2} &= -\frac{3rt\Delta E}{2} \\
\sigma^2_{m_\nu^2} &= \frac{2}{3rt\Delta E}\sqrt{N_{\rm tot}} \\
&\simeq \frac{2}{3rt}\sqrt{rt\Delta E + \frac{bt}{\Delta E}}
\end{aligned}$$

There is an optimum choice of ΔE that minimizes the uncertainty,

$$\Delta E_{\rm opt} = \sqrt{\frac{b}{r}}. \tag{5}$$

The minimum is broad. As a practical matter, it may not always be possible to achieve an instrumental width of the optimum size when rates are high or backgrounds low. Moreover, improving the instrumental resolution beyond a certain point is not useful because there is a limit set by the broadening caused by the final-state spectrum (FSS) in the decay of molecular T_2 to T^3He^+. The FWHM of this distribution is about 1 eV [15]. The instrumental resolution itself has two readily identifiable components, the field inhomogeneity and the finite duration of a cyclotron-emission wave-train before the electron scatters. To allow for these contributions, we adopt a composite analysis window width

$$\Delta E = \sqrt{\frac{b}{r} + (\Delta E_{\rm FSS})^2 + \left(\frac{E}{(\gamma-1)}\frac{2.35\sigma_B}{B}\right)^2 + \left(\frac{E}{(\gamma-1)}\frac{2.35\beta c\sigma_0 n}{2\pi f_{\rm c}}\right)^2} \tag{6}$$

where $\Delta E_{\rm FSS}$ is a minimum useful width set by final-state broadening, σ_B is the rms field variation in the active region, σ_0 is the scattering cross section per molecule, n is the number of molecules per unit volume, β is the velocity of the electron, and $f_{\rm c}$ is the cyclotron frequency. The contribution due to scattering is neither Gaussian nor Lorentzian when short wave-trains are rejected as they would be experimentally; a Gaussian is assumed here for convenience.

The decay rate R in a volume V is related to the number density n through the mean lifetime τ_m,

$$R = n\frac{V}{\tau_m}. \tag{7}$$

Electrons with a shallow pitch angle, smaller than $\theta_{\rm min}$, are not trapped, introducing a solid angle $\Delta\Omega$, where

$$\sin\theta_{\rm min} = \sqrt{\frac{B}{B_{\rm max}}} \tag{8}$$

and $\frac{B}{B_{\rm max}}$ is the ratio of the maximum trapping ("pinch") field at the center of the trap. Hence

$$\begin{aligned}
\Delta\Omega = 4\pi\cos\theta_{\rm min} &= 4\pi\sqrt{1-\frac{B}{B_{\rm max}}}, \\
r &= \frac{\Delta\Omega}{4\pi}\frac{nV}{\tau_m}\eta,
\end{aligned}$$

where r is the detected decay rate and η is the branching ratio to the uppermost 1 eV of the spectrum ($\sim 2\times 10^{-13}$). Other contributions to inefficiency can be merged and the solid angle becomes a general efficiency.

In addition to the statistical uncertainty arising from the term b/r in Eq. 6, there are systematic contributions attributed to the width of the FSS distribution, the field inhomogeneity, and the collision-broadening. Each of the resolution components in Eq. 6 has an associated uncertainty that propagates into the neutrino mass. For concreteness, we assume that the distributions are each known to 1%. There is a simple relationship [16] between the uncertainty

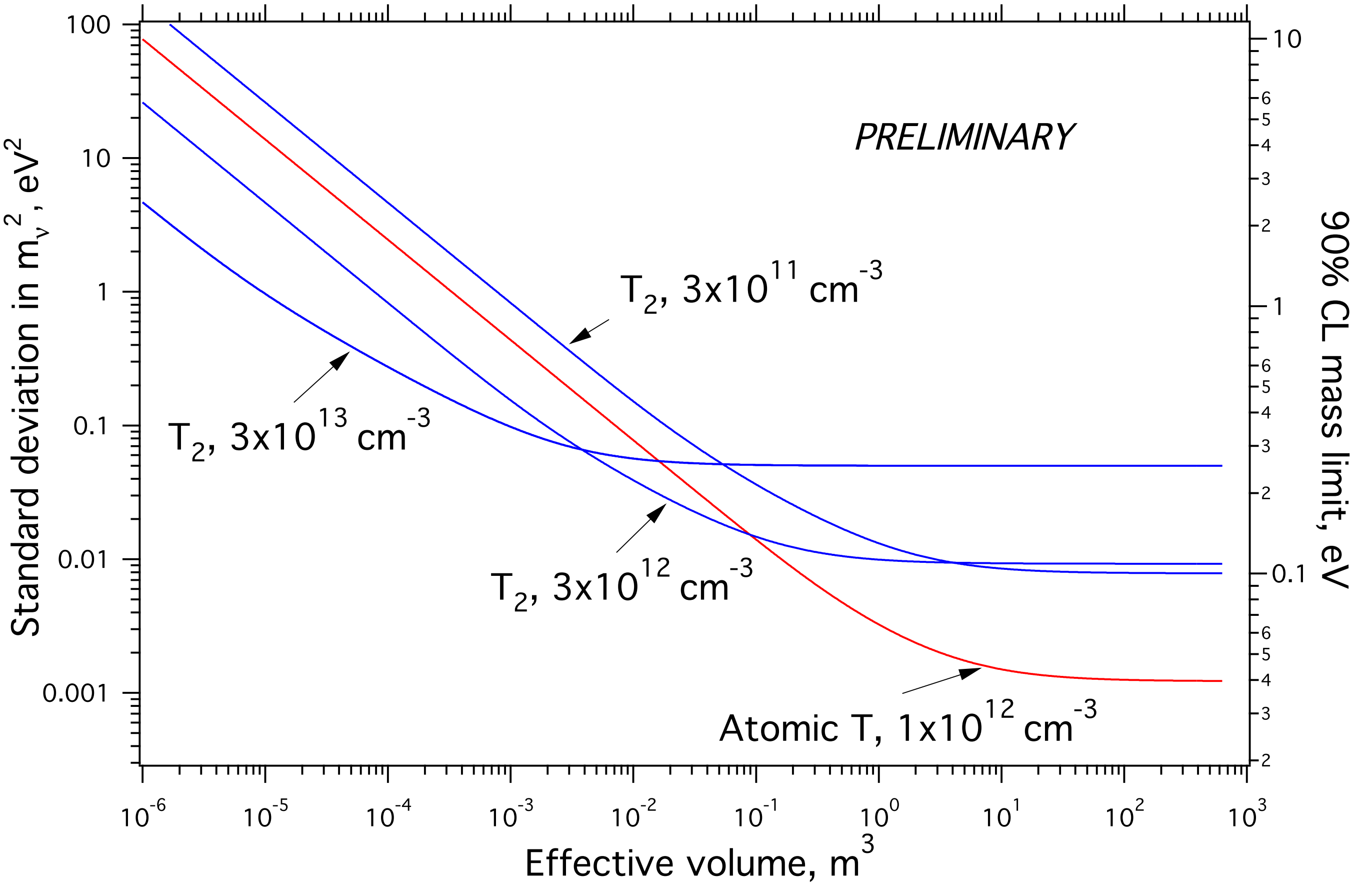

FIG. 1: Uncertainty obtainable as a function of volume under observation for various choices of number density per cm^3. Systematic uncertainties due to imperfect knowledge of contributions to the resolution are included. The frequency chosen is 26.5 GHz, the field is uniform to 0.1 ppm rms, the source temperature for molecular T_2 is 30 K and for atomic T it is 1 K, and the background is 10^{-6} per second per eV. The efficiency factor $\Delta\Omega/4\pi$ is taken as unity for the effective volume, and the live time is 3×10^7 seconds.

$\sigma_{\rm res}$ in the width of an instrumental resolution contribution and the corresponding uncertainty introduced in the neutrino mass:

$$\sigma^2_{m^2_\nu} \simeq 2\sigma^2_{\rm res} \tag{9}$$

Figure 1 shows calculated neutrino mass statistical and systematic sensitivities for various choices of number density, as a function of volume. For calculating the sensitivity shown here, the expected value for m^2_ν is taken to be 0, and, statistically, positive and negative values for this quantity are equally probable. The 90% C.L. is a one-sided interval derived by setting the 1.28-sigma upper threshold on m^2_ν , which is assumed to be Gaussian distributed. The square root of this number is displayed on the right-hand axis.

As can be seen, an experiment with gaseous molecular T_2 reaches a limit in sensitivity of order 100 meV because of the width of the FSS combined with Doppler broadening associated with the minimum feasible operating temperature near 30 K. For this reason, the Project 8 collaboration is developing an atomic T source in a magnetic configuration that traps both spin-polarized atoms and the betas. The density required is in an achievable range, and the operating temperature needed is of order 1 K.

The physics reach of a Project 8 experiment depicted in Fig. 1 is attractive, but should be regarded as about the best that could be done with this type of measurement. The systematic uncertainties assumed on resolution-like parameters are small and a number of presumably less important effects are omitted.

IV. PROJECT 8: A PHASED APPROACH

The development of Project 8 is being carried out in Phases with well-defined objectives at each step. The first phase is a proof of principle, to show that the free radiation from a single electron at the cyclotron frequency can be detected and measured. For this phase, we utilize the decay of $^{83\mathrm{m}}$Kr as our electron source. The radioactive isotope $^{83\mathrm{m}}$Kr is a gamma-emitting isomer of ^{83}Kr with a half-life of 1.8 h, in which internal conversion produces mono-energetic electron lines with kinetic energies of 17 830.0(5) eV, 30 227(1) eV, 30 424(1) eV, 30 477(1) eV and 31 942(1) eV. Our first objective has been detection of those lines, and then a precise measurement of their energies. Following confirmation of the detection principle, the next phase is a small-scale tritium experiment with a mass sensitivity of order 10 eV to show that the method can be used to measure the beta spectrum, and to explore the method's scalability. The experiment would both serve as the prototype for a much larger one, and also provide physics results with very different systematics compared to existing experiments.

TABLE II: List of the main stages of the Project 8 experiment.

Phase:	I	II	III	IV
Timeline	2010-2014	2014-2016	2016-2017	2018+
Science Goals	Proof of Principle; Kr Spectrum	T-He Mass Difference	$m_\nu < 2$ eV	$m_\nu < 0.2$ eV
Source	^{83m}Kr	Molecular ^{3}H	Molecular ^{3}H	Atomic ^{3}H
R & D Milestones	Single electron detection	Tritium spectrum	High rate sensitivity	

Each stage of this phased approach provides both the necessary R&D and key physics measurements of interest to the physics community. A summary of the various stages of the experiment, along with key scientific milestones as the program as a whole builds toward a sensitive neutrino mass measurement, are listed in Table II.

A. Results from Phase I

The Project 8 collaboration has designed and constructed a small-volume prototype (Phase I from the above timeline) experiment to demonstrate the feasibility of single-electron RF detection. The prototype has been built at the University of Washington with strong participation from MIT, University of California Santa Barbara, and Pacific Northwest National Laboratory. The prototype incorporates all the main features of the envisioned full-scale experiment: a gaseous electron source, a magnetic trapping region, and the RF detection and amplification scheme. The trap is small, a section of WR-42 waveguide (about 6 mm x 10 mm in cross section) with a copper coil wrapped around it. A uniform axial field of 0.945 T is produced by a Bruker 200 superconducting magnet. The harmonic trap coil imposes an approximately parabolic local perturbation on the uniform field, and electrons that are produced in that region with a pitch angle of 90 ± 5 degrees can be trapped. The trap depth can be adjusted to be up to about 1% of the main field.

The first full test of the new system was carried out on June 6, 2014. Within the first second of data-taking, cyclotron radiation from trapped electrons was clearly seen. The data can be displayed in a waterfall plot of bins of frequency on the y-axis against time on the x-axis (Figure 2). The intensity is shown on a color scale indicating Fourier-transform power within a bin.

The electron can be seen going through a process of continuous energy loss due to cyclotron radiation, which causes each linear segment to tilt upwards slightly to the right, interspersed with abrupt scattering events from residual gas molecules causing energy losses that are typically about 14 eV. Because the electron is in a harmonic trap, the cyclotron frequency depends on the pitch angle, which changes after each scattering. Hence some scatters can decrease the cyclotron frequency if the increase in pitch angle more than compensates for the energy loss. The amount of detail in these spectrograms was a surprise, as it was expected that scattering events would almost always eject the electron from the trap. Evidently the scattering angle in most interactions is very small. The long intervals, hundreds of μs, between scatters indicate the background pressure in the cell is $< 10\mu$Pa.

An analysis of the frequency onset of these events also reveal the spectroscopic capabilities of the technique. Figure 3 shows the kinetic energy distribution from the $^{83\mathrm{m}}$Kr source; the 17, 30 and 32 keV emission lines can clearly be identified. A fit to the frequency distribution yields a full width at half maximum of approximately 140 eV. An apparatus designed to optimize resolution will be able to significantly decrease these uncertainties, which do not represent fundamental limits. Indeed, subsequent data taken at shallower trap configurations show further narrowing of the resolution, where the 30 keV doublet distribution can clearly be identified.

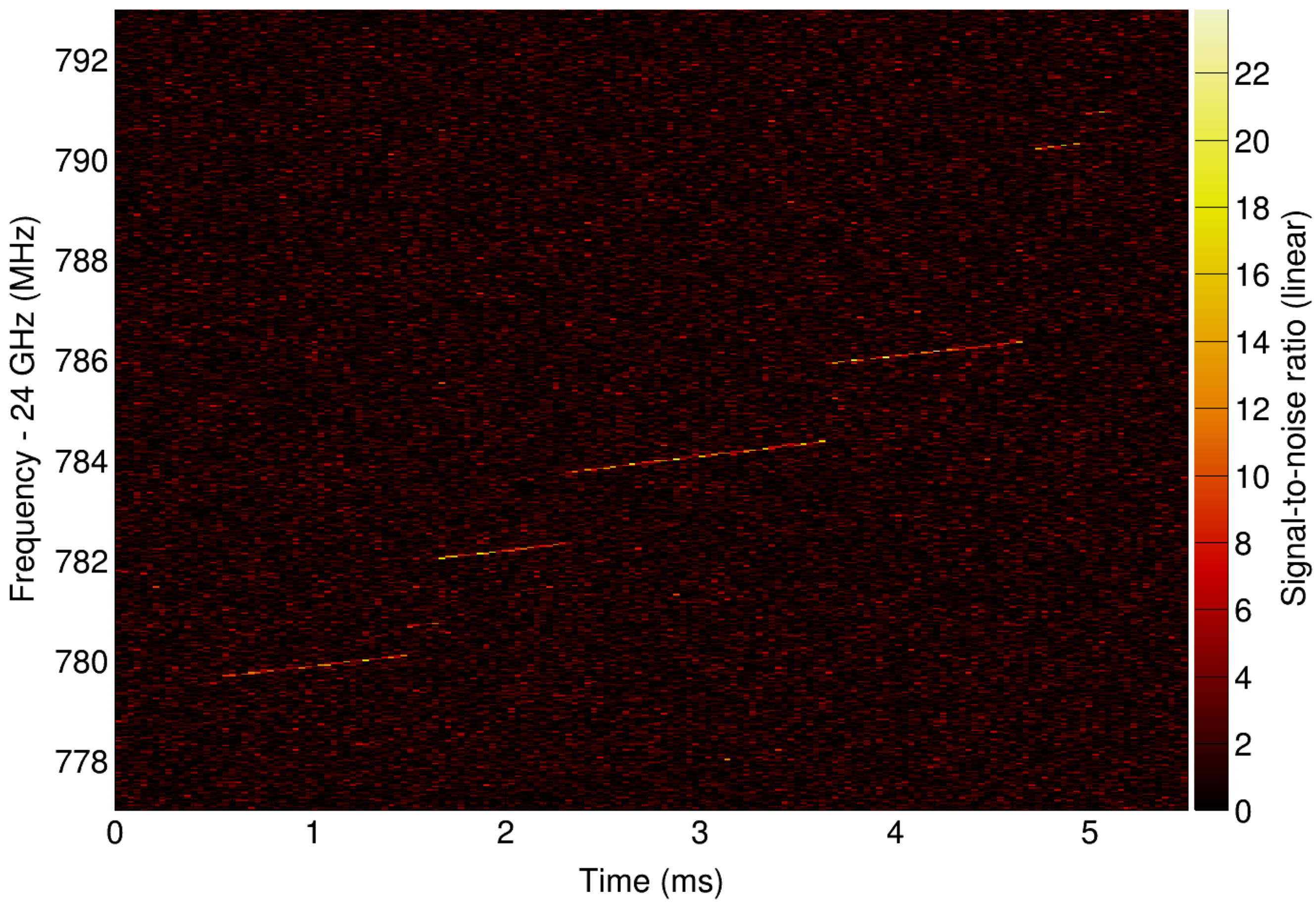

FIG. 2: A typical signal from the decay of ^{83m}Kr characterized by an abrupt onset of narrowband power over the thermal noise of the system. The measured frequency reflects the kinetic energy of the electron, in this case 30 keV. The frequency increases slowly as the electron loses energy by emission of cyclotron radiation, ending in the first of six or possibly seven visible frequency jumps before the electron is ejected from the trap. The frequency-time window shown represents only a portion of an extended event lasting more than 15 ms. The sudden jumps result from the energy loss and pitch-angle changes caused by collisions with the residual gas, predominantly hydrogen. The most probable size of the energy jump, as determined from many events, is 14 eV.

V. SUMMARY

With the successful demonstration of the principle of Project 8, we begin the transition to Phase II, in which a tritium spectrum in a small-scale system is to be obtained. Such a measurement would establish the applicability of the technique toward beta decay measurements as well as determine the scalability of the technique toward larger volumes. It appears at this time that a measurement of the neutrino mass in the presently unknown regime below 2 eV can be made with this technique. Given the extremely strong scientific impact of probing neutrino masses down to the inverted hierarchy region, the collaboration will also begin R&D studies for transitioning to atomic tritium. Our collaboration believes this technique opens the possibility of pushing neutrino mass sensitivity down toward the coveted region of the inverted scale and, in so doing, resolving one of the important outstanding questions in neutrino physics.

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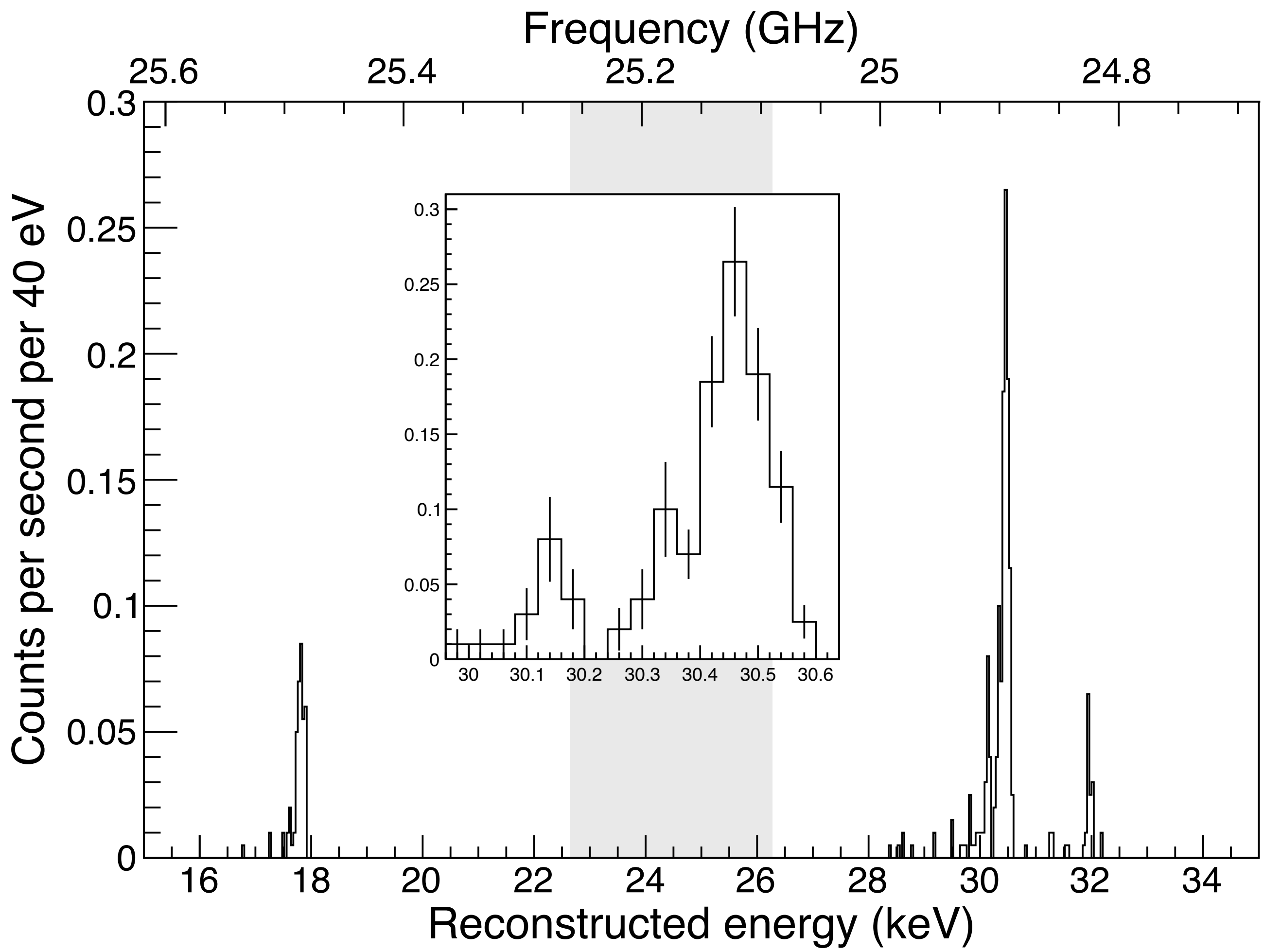

FIG. 3: The kinetic energy distribution of conversion electrons from $^{83\mathrm{m}}$Kr as determined by cyclotron frequency. The spectrum shows the 17 keV, 32 keV and 30 keV-complex conversion electron lines. The shaded region indicates the bandwidth where no data were collected. Insert: An expanded view of the 30 keV energy region, where the 30.4 keV conversion electrons can be seen.

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