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Measuring Neutrino Masses Using Radio-Frequency Techniques

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Abstract. We describe a new technique by which the energy spectrum of low energy electrons can be extracted. The technique relies on the detection and measurement of coherent radiation created from the cyclotron motion of charged particles, such as electrons, in strong magnetic fields. The technique proposed relies on the principle that the frequency of cyclotron radiation emitted by the particle depends inversely on its Lorentz boost. Detection and measurement of the coherent radiation emitted is tantamount to measuring the kinetic energy of the electron. As the technique inherently involves the measurement of a frequency in a non-destructive manner, it can, in principle, achieve a high degree of precision and accuracy; estimated to be better than 1 part in 10^6 for electrons with kinetic energies between 5 and 50 keV. One immediate application of this technique is in the measurement of the endpoint spectrum from tritium beta decay, which is directly sensitive to the absolute mass scale of neutrinos.

1. Motivation

Ever since Enrico Fermi's original proposal[Fermi(1933)], it has been known that the neutrino mass has an effect on the kinematics of beta decay. Measurements have always suggested that this mass was very small, with successive generations of experiments giving upper limits[Weinheimer et al.(1999)][Lobashev et al.(2001)], most recently $m_{\nu\beta} < 2.3$ eV. The upcoming KATRIN experiment[Angrik et al.(2005)][Osipowicz et al.(2001)] anticipates having a sensitivity of 0.20 eV at 90% confidence. If the neutrino mass is much below 0.20 eV, it is difficult to envision any classical spectrometer being able to access it. Oscillation experiments, however, tell us with great confidence that the tritium beta decay neutrinos are an admixture of at least two mass states, at least one of which has a nonzero mass, such that the effective mass must satisfy $m_{\nu\beta} > 0.005$ eV under the normal hierarchy or $m_{\nu\beta} > 0.05$ eV in the inverted hierarchy. These bounds provide a strong motivation to find new, more sensitive ways to measure the tritium beta decay spectrum.

The most sensitive direct searches for the electron neutrino mass up to now are based on the investigation of the electron spectrum of tritium β-decay. The electron energy spectrum of tritium β-decay for a neutrino with component masses m_1, m_2, and m_3 (with mixing angles U_{e1}, U_{e2}, and U_{e3}, respectively) is given by

$$\frac{dN}{dE} = C \times F(Z, E) p E (E_0 - E) \sum_{i=1,3} |U_{ei}|^2 [(E_0 - E)^2 - m_i^2]^{\frac{1}{2}} \Theta(E_0 - E - m_i), \qquad (1)$$

where E denotes the electron energy, p is the electron momentum, E_0 corresponds to the total decay energy, $F(Z, E)$ is the Fermi function, taking into account the Coulomb interaction of the

outgoing electron in the final state, $\Theta(E_0 - E - m_i)$ is the step function that ensures energy conservation, and C is a constant. As both the matrix elements and $F(Z, E)$ are independent of m_ν, the dependence of the spectral shape on m_ν is given by the phase space factor only. In addition, the bound on the neutrino mass from tritium β-decay is independent of whether the electron neutrino is a Majorana or a Dirac particle.

To make advances toward lower and lower masses, it is important to develop techniques that allow for extremely precise spectroscopy of low energy electrons. The technique proposed here relies on the principle that the frequency of cyclotron radiation emitted by the particle depends inversely on its energy, independent of the electron's direction when emitted. As the technique inherently involves the measurement of a frequency in a non-destructive manner, it can, in principle, achieve a high degree of resolution and accuracy. The combination of these two features makes the technique attractive within the context of neutrino mass measurements.

2. Description of the Technique

Imagine a charged particle, such as an electron created from the decay of tritium or from neutrino capture, traveling in a uniform magnetic field B. In the absence of any electric fields, the particle will travel along the magnetic field lines undergoing simple cyclotron motion. The characteristic frequency ω at which it precesses is given by

$$\omega = \frac{eB}{\gamma m_e} = \frac{\omega_c}{\gamma} = \frac{\omega_c}{1 + \frac{K_e}{m_e c^2}}, \tag{2}$$

where ω_c is the cyclotron frequency, K_e and m_e are the electron kinetic energy and mass, respectively, and γ is the relativistic boost factor. The cyclotron frequency, therefore, is shifted according to the kinetic energy of the particle and, consequently, any measurement of this frequency stands as a measurement of the electron energy. Since the relativistic boost for the energies being considered is close to unity, the radiation emitted is relatively coherent. For a magnetic field strength of 1 T, the emitted radiation has a frequency of 27 GHz. This frequency band is well within the range of commercially available radio-frequency antennas and detectors. It is conceivable, at least in principle, to make use of such radio-frequency detection techniques in order to achieve precision spectroscopy of single electrons.

Consider the arrangement shown in Fig. 1(a). A low-pressure supply of tritium gas is stored in a uniform magnetic field generated by a solenoid magnet. Tritium decay events release electrons with $0 < E_e < 18575$ eV (and velocity $0 < \beta < \beta_e$ where $\beta_e = 0.2625$) in random directions θ relative to the field vector. The electrons follow spiral paths with a velocity component ($\beta_{||}$) parallel to the magnetic field. Each electron emits microwaves at frequency ω as defined in Eq. 2 and a total power which depends on $\beta_{||}$ and $\beta_\perp$. This allows, at least in principle, the extraction of the electron spectrum. A more in-depth description of the technique, including a discussion of its potential sensitivity, can be found in Ref [Monreal and Formaggio(2009)].

3. Current Activities

Since 2010, a small collaboration has been formed to demonstrate the feasibility of the technique and build toward a new neutrino mass experiment. The collaboration, known as Project 8, includes members at the California Institute of Technology, the Karlsruhe Institute of Technology, Haystack Observatory, the Massachusetts Institute of Technology, the National Radio Astronomy Observatory, Pacific Northwest National Laboratory, University of California, Santa Barbara, and the University of Washington.

A prototype test vessel that has been constructed by the collaboration at the University of Washington to test the feasibility of the technique. The prototype incorporates all the main features of the envisioned full-scale experiment: a gaseous electron source, a magnetic
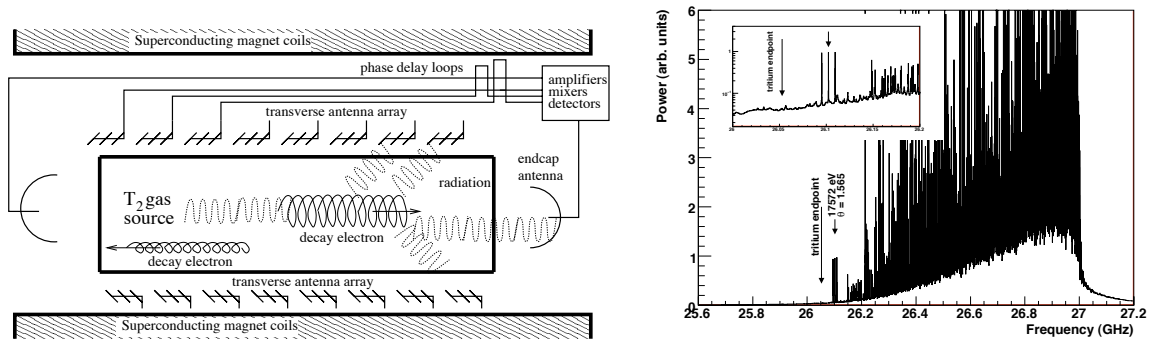
Figure 1. Left: Schematic of the proposed experiment. A chamber encloses a diffuse gaseous tritium source under a uniform magnetic field. Electrons produced from beta decay undergo cyclotron motion and emit cyclotron radiation, which is detected by an antenna array. Right: Simulated microwave spectrum, showing the cyclotron emission of 10^5 tritium decays over $30\mu s$ in a 10m long uniform magnet ($B \sim 1$ T) with a finely-spaced transverse antenna array. e^--T_2 scattering is neglected. The short arrow points out a triplet of spectral peaks generated by an individual high-energy, high pitch angle electron. The log-scale inset zooms in on this electron and the endpoint region.

trapping region, an RF antenna and amplification scheme. The gaseous source in this case uses ^{83m}Kr, which emits mono-energetic electrons at 17.8 and 32 keV kinetic energy, providing a well-known calibration source for the experiment. The ^{83m}Kr source was produced at the Center for Experimental Nuclear Physics and Astrophysics (CENPA) at the University of Washington by irradiating a gas cell of ^{nat}Kr with an intense 17.5 MeV proton beam. The (p, n) reaction produces ^{83}Rb which then provides a continuous source of ^{83m}Kr. The Kr cell was irradiated for 244 μA-hr for a total yield of 0.8 mCi of ^{83}Rb. The subsequent Rb activity was measured using a germanium detector. The krypton gas is injected in the detector volume at low pressure ($\simeq 10^{-7}$ mbar) and is monitored through the use of a residual gas analyzer.

A small fraction of the electrons from the decay of ^{83m}Kr will be ejected within the center of the cavity chamber. Electrons with sufficiently high pitch angles created in this region are trapped within a small magnetic bottle so as to extend the observation of the cyclotron emission. Both signal-to-noise and energy resolution improve with trapping time. The primary 1 Tesla magnetic field (which determines the overall cyclotron frequency) is produced by a cold-bore superconducting magnet. The trapping field is provided by a small insert coil which provides a harmonic potential within the center of the magnet. The 0.01 T/cm^2 correction coil allows for trapping of electrons with pitch angles between 89 and 90 degrees from the main magnetic field axis (about 2% of all ^{83m}Kr decays). The field strength is monitored using a Hall probe and has a homogeneity of $\sim 10^{-4}$. In addition to the gas analysis performed with the residual gas analysis, an independent check of the electrons ejected from the ^{83m}Kr decay is made using a pin diode detector.

The trapping volume is constructed from a section of WR-42 waveguide isolated by a Kapton window from another section of waveguide. The waveguide antenna is coupled to a cryogenic RF amplifier with 15 K internal noise. The signal is filtered and brought to room temperature, where it is mixed with a 24.500 GHz local oscillator and further amplified at lower frequencies. The full amplification chain provides about 80 dB of amplification in the frequency range of 25.2-25.5 GHz. The system is capable of digitizing one channel of data with zero dead time up to a sampling rate of 750 MHz, where each sample is one byte long. The slow control system is read out onto a separate machine which maintains a CouchDB database of all values, each of
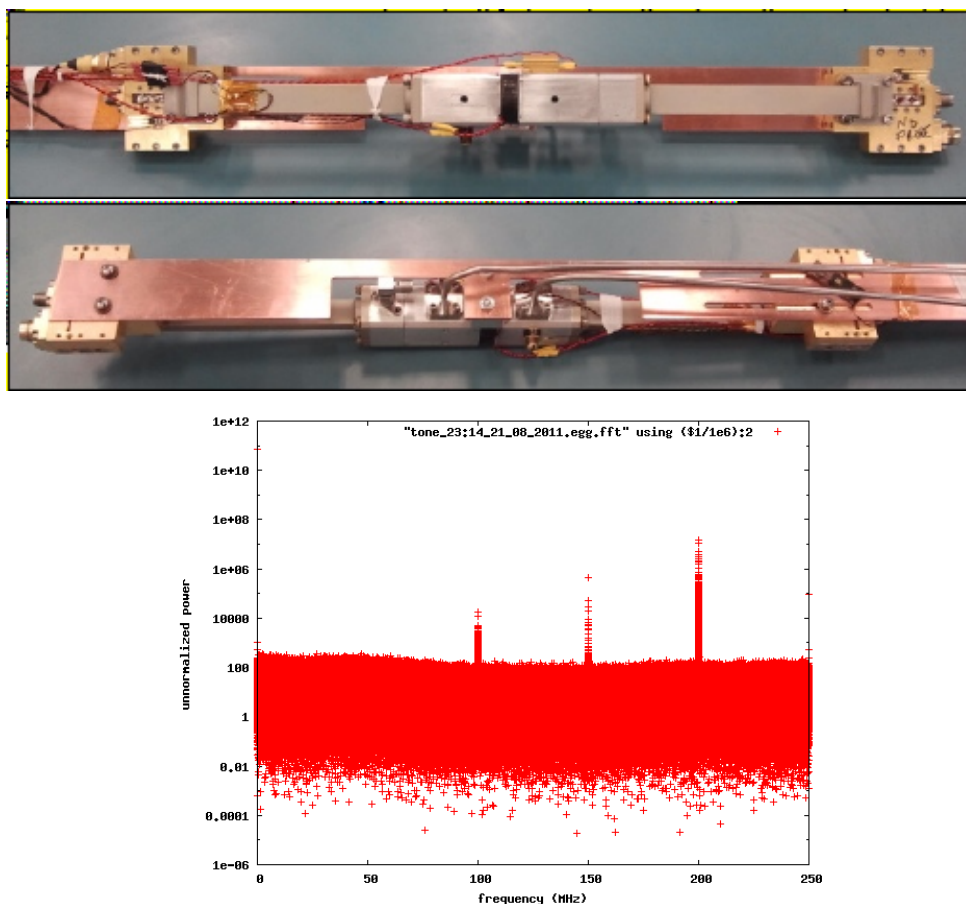
Figure 2. Top: Photograph of waveguide front and rear antennae. The main chamber is flanked by two WR-42 guide assemblies attached to cryogenic amplifiers. Bottom: Tone calibration data taken with the Project 8 prototype system. Tone introduced at 26 GHz and mixed down to 150 MHz can be seen at the center frequency. Two background tones (at 100 and 200 MHz) also visible in power-frequency spectrum.

which is taggable for future lookup and reference. A full Monte Carlo of the prototype response has been developed. The simulation includes many of the known effects associated with the cyclotron signal, including energy losses, Doppler shift effects, reflections, ambient noise, and reflections.

Commissioning of the gas delivery, magnet, and amplification chain commenced in August 2011. In September, 2011, first data with the prototype were collected at 1 T field. A total of 4 TB of digitized waveform data was collected and stored (about 4 hours of total exposure). Analysis of the data collected from this and subsequent runs is ongoing.

4. Bibliography

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