Project 8

Determining the neutrino mass with Cyclotron Radiation Emission Spectroscopy

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for the Project 8 Collaboration
An Admiral Stockdale Moment...
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“Who am I? Why am I here?”
Our “Periodic” Table...
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Since the beginning, the neutrino was an odd one...

Neutrino mass measurements have a long history in physics, predating the Standard Model itself.

It should therefore be no surprise that our quest to understand this fundamental property continues; both for its own right as well as its theoretical implications.
With oscillations firmly in place, we at least understand that the neutrino has a mass. As such, oscillation measurements place a lower limit on the neutrino mass scale.
2015 Nobel Prize in Physics

Arthur B. McDonald
(Sudbury Neutrino Observatory)

Takaaki Kajita
(Super-Kamiokande)
The legacy...

\[ M = \sum_{i}^{n_{\nu}} m_{\nu,i} \]

Cosmological Measurements

\[ \langle m_{\beta\beta}^2 \rangle = \left| \sum_{i}^{n_{\nu}} U_{ei}^2 m_{\nu,i} \right|^2 \]

0νββ Measurements

\[ \langle m_{\beta} \rangle^2 = \sum_{i}^{n_{\nu}} |U_{ei}|^2 m_{\nu,i}^2 \]

Beta Decay Measurements

Qian and Vogel, Progress in Particle and Nuclear Physics 83 (2015).
\[ \dot{N} \sim p_e (K_e + m_e) \sum_i |U_{ei}|^2 \sqrt{E_0^2 - m_{\nu i}^2} \]

\[ ^3H \rightarrow ^3He^+ + e^- + \nu_e \]

**Beta Decay**

A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass

Look for a kink in the electron spectrum
Project 8

Coherent radiation emitted can be collected and used to measure the energy of the electron in non-destructively.

“A. L. Schawlow

“If you are going to measure anything with precision, measure frequency!”

A. L. Schawlow

Coherent radiation emitted can be collected and used to measure the energy of the electron in non-destructively.

“Never measure anything but frequency.”
I. I. Rabi

A. L. Schawlow

Frequency Approach

\[ ^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \nu_e \]
CRES Technique

Novel technique of Cyclotron Radiation Emission Spectroscopy (CRES):

- Cyclotron radiation from single e\(^-\) in magnetic field
- Source gas transparent to microwave radiation
- No e\(^-\) transport from source to detector (gas scattering)
- Highly precise frequency measurement

\[
f_c = \frac{1}{2\pi} \frac{eB}{m_e + K/c^2}
\]

For 1 T field, emission is at 26 GHz.

Techniques common to radio astronomy can be used for signal detection.

B. Monreal and JAF, Phys. Rev D80:051301
The Radiation from an Electron describing a Circular Orbit.

The complete formula for the radiation may be useful to some of those who are now indulging in atomic speculations. It is derived from the general formula I gave a year ago in Nature (October 30, 1902), expressing the electromagnetic field everywhere due to an electron moving anyhow. Put in the special value of $R$ required, which is a matter of elementary geometry, and the result is the complete finite formula. But only the part depending on $R^{-1}$ is required for the radiation; and, in fact, we only want the $r^{-1}$ term (if $r=$ distance from the centre of the orbit), if the ratio of the radius of the orbit to the distance is insensible, and that, of course, is quite easy, on account of the extreme smallness of electronic orbits. The magnetic force is given by

$$H_x = \frac{Qun}{4\pi rv} a^3 \cos \theta \cos \phi_1,$$

$$H_y = \frac{Qun}{4\pi rv} a^3 (\sin \phi_1 - \beta),$$

subject to

$$\alpha = \frac{1}{1 - \beta \sin \phi_1}, \quad \beta = \frac{\alpha}{v} \sin \theta,$$

$$\phi_0 = \phi_1 + \beta \cos \phi_1 = \phi - nt + nr/v.$$ 

There is no limitation upon the size of $u/v$, save that it must be less than 1. But there is a limitation regarding...
Basic Layout of Our Prototype

- **Gas/Electron System**
  Provides mono-energetic electrons for signal detection.

- **Magnet System**
  Provides magnetic field and trapping of electrons.

- **RF Detection/Calibration System**
  Detection of microwave signal.
The Apparatus

Cyclotron frequency coupled directly to standard waveguide at 26 GHz, located inside bore of NMR 1 Tesla magnet.

Magnetic bottle allows for trapping of electron within cell for measurement.
Phase I setup is a waveguide setup for single electron detection (about 1 fW power emission)
Cyclotron Radiation Emission Spectroscopy (CRES) for single relativistic electrons now experimentally demonstrated.
Project 8's "Event Zero"

Electron scatters of gas, losing energy and changing pitch angle.

Energy loss increases frequency.

Onset frequency yields initial kinetic energy.


Exhibits all predicted characteristics:

- Onset frequency
- Energy loss due to cyclotron radiation
- Quantum jumps due to inelastic scattering
Imaging of mono-energetic electrons show excellent precision and resolution of expected electron lines (about 3.6 eV FWHM).

Shown to be a powerful spectroscopic tool for radioactive gasses.
We are now moving toward a competitive neutrino mass measurement using this technique.

First tritium run starts this year.

Next Stage:
Phase II
(Tritium Cell)

BDPA Magnetometers
waveguide short

$B \sim 1T$

We are now moving toward a competitive neutrino mass measurement using this technique.

First tritium run starts this year.
Final Goals

Phase III

- Multiple antennas to provide detection in large volume.
- Sensitivity goal of ~2 eV.

Phase IV

- Move to large volume (m$^3$) atomic tritium target.
- Goal to reach inverted mass ordering scale.
The Radio Astronomy Overlap

ROACH2 planned for Phase II data taking

Complex frequency event reconstruction, multiple antennas.