Determining Absolute Neutrino Mass using Quantum Technologies

Before diving into the specific experimental approaches to electron spectrometry required for measuring the ß-decay electron spectra of atoms, first I would like to explain the key physical principle it relies on: cyclotron radiation.

Cyclotron Radiation (pg. 11)

- A cyclotron is a particle accelerator consisting of two semicircular electrodes called dees that are electrically insulated from each other and connected to the two terminals of an oscillator which supplies the system with an alternating voltage; they are separated by a narrow gap inside a vacuum chamber between the poles of a magnet.
  - You want them **electrically insulated** so that the alternating voltage can be applied between them, and therefore create the oscillating electric field across the gap which is needed to accelerate the particles. If they weren't they would be in the same potential, so no electric field between them (think of capacitor plates, where each is connected to opposite sides of a high-frequency voltage source, and the gap between is where the E-field exists).
  - The dees are inside a vacuum chamber to avoid particle collisions with uncharged particles like air molecules because they can scatter the accelerated ions, can slow them down and dissipate their energy, or knock them off course. So vacuum is needed for the particles to spiral freely without interacting/colliding with anything outside, so the acceleration is efficient and clean.
  - The particles are created in the centre: there's a small ion source in the middle of the cyclotron right between the dees. And this source contains a low-pressure gas like Hydrogen if you want to accelerate ions. So the high-voltage discharge ionises the gas and creates positive ions right at the centre which are then accelerated immediately by the electric field in the gap between the dees. Cyclotrons almost always accelerate positive ions.
- The electric field in the gap propels the particles into one of the dees and the magnetic field which is perpendicular to the plane of the dees and the direction of their motion, guides them in a half-circle path and then it comes back to the gap.
- Thanks to the alternating voltage, by the time the particle reaches the gap, the electric field has reversed the polarity, so the particles are accelerated into the

other dee with more speed. And this repeats again and again, each time the particle crosses the gap, its energy increases and the spiral gets larger. As long as the magnetic field remains constant and we stay in the non-relativistic regime, so we avoid the relativistic effects, these crossings occur at a fixed frequency. (otherwise the cyclotron frequency would decrease due to the relativistic increase of the mass)

- Once the accelerated particle or ion has enough energy, it strikes a target material after leaving the spiral path. It's used to induce nuclear reactions, like produce radioactive isotopes in medical imagining or deliver energy for medical therapy like hitting a human tissue etc.
  - The deflection plate is negatively charged so it attracts the positive ion and pulls it out of the spiral path.
- The EM radiation emitted during this acceleration is called the cyclotron radiation where the frequency of the radiation is the same as the cyclotron frequency

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Cyclotron Radiation Emission Spectroscopy (pg. 13)

This introduced a new approach for measuring the kinetic energies of ß-decay electrons in molecular tritium experiments at that time.

They show that a new type of electron energy spectroscopy could improve future measurements of the energy spectrum, and therefore of the neutrino mass, and future experiments actually did.

  - The measurements of cyclotron frequencies of low-energy leptons have played a central role in the determination of electron and positron g-factors, in the production of positronium and antihydrogen etc.

- Their idea is to detect **cyclotron radiation** from mildly relativistic electrons generated from the decay of a diluted molecular tritium source, where the frequency now depends on the energy.

The experimental arrangement is as follows:

- A diluted, low-pressure supply of tritium gas is stored inside a chamber under a uniform magnetic field (0.5-1T) generated by a solenoid magnet.
- The gas undergoes a ß-decay, emitting electrons up to 18.6 keV energy.
- The magnetic field causes the electrons to move in spiral trajectories, with a frequency that depends on their energy (the Lorentz factor) but not on the angle between the electron's velocity and the direction of magnetic field.

- As they spiral, electrons emit microwave radiation where the higher-energy electrons will emit cyclotron radiation at a slightly lower frequency, so this tiny relativistic shift is measurable and it can allow to extract the energy of the emitted radiation. And by measuring the energy, the shape of the ß-spectrum near the endpoint can be reconstructed and the neutrino mass can be constrained.
- The detection of the signal depends on the antenna configuration. So they discuss two configurations:
- **1. Antennae end-caps**
  - Here the tritium source is placed inside a waveguide (a hollow metal tube) that collects the microwaves towards the end of the tube where the antennae are.
  - As the electrons have a velocity component which is parallel to the direction of the magnetic field, a Doppler shift happens, where the antenna where the electron is moving toward to will see a blueshift because it sees a higher frequency, and the other antenna will see a redshift because the electron is moving away from it. By detecting both shifts, the electron energy and the pitch angle can be uniquely determined.
- **2. Transverse Antennae array**
  - Here, an array of evenly-spaced antennae is placed along the length of the chamber, so perpendicular to the magnetic field.
  - Each antenna sees a short pulse signal as the electron passes by which sweeps from blueshift to redshift. But the sum of the signals by all antennas should give a clear final signal that appears as a “carrier wave” with a frequency equal to the cyclotron frequency.
  - The energy of the electron is computed from the frequency.
  - The energy spectrum can be reconstructed and the endpoint shape can reveal the neutrino mass.
  - Phase delay loops are electronic circuits used to correct for the fact that any given moment, the electrons are physically closer and further apart from the transverse array of antennae. Without correction, you would get a distorted signal due to phase mismatches, the cyclotron frequency would be smeared or even cancelled by destructive interference. So you want to synchronise the signal from the transverse antennae array so that the true cyclotron frequency adds up coherently.

- This technique is really the heart of new generation of absolute neutrino mass experiments like Project 8 and QTNM. It is also part of PTOLEMY experiment's plan to measure relic neutrinos.
- The technique can be implemented over a wide range of kinetic energies, including those around the endpoint of ß-decay spectrum of tritium at 18.6 keV.
- It can be implemented by enclosing the measurement region in the CRES spectrometer in a waveguide surrounding it by arrays of antennas. All components can be optimised for the frequency of interest to maximise the collection efficiency. Using standard approaches of microwave frequency metrology, it allows for precise determination of the cyclotron frequency of single electrons.

To use atomic sources of ß-decay electrons in CRES spectrometer comes with its challenges: (pg. 15)

- Requirements:
    - High phase-space density atomic tritium sources: atomic tritium is very reactive and tends to recombine into molecular tritium. So in order to have enough ß-decays per unit time (statistics), minimal scattering, and a clean spectrum, we need a cold, dense and pure atomic gas.
    - Long observational time for individual electrons: because in order to achieve high energy resolution, you need to detect the cyclotron frequency for a long time because electrons can collide with atoms or drift out of the detection volume.
- 1. To precisely determine the kinetic energies of electrons from the frequency of the emitted cyclotron radiation, the magnetic field needs to be known with extreme precisions.
  The cyclotron frequency depends directly on the magnetic field, so any variation or uncertainty is directly introduced in the frequency and the inferred energy. So it is essential to precisely map the magnetic field distribution throughout the whole measurement region, meaning that you need to measure the strength and the shape of the magnetic field at every point in the experimental volume with extremely fine resolution.
  This is demanding and overall difficult because the experiment operates at 4K to minimise thermal noise and it limits available sensors, as it changes material behaviour and complicates calibration.
- 2. Need to minimise uncontrolled electric fields which do not arise from the applied voltage but from imperfections of the instrumented region. They can

distort the electron's trajectory as it spirals over the magnetic field, can cause non-uniform acceleration, shifting the cyclotron radiation frequency and reducing the precision of the energy measurement.
Since CRES is focused on precision measurements of the frequency, it's important to avoid systematic errors in the electron energy and in the absolute neutrino mass.

The work done so far using this technique, paves the way for future experiments directed toward determination of electron kinetic energies to a precision of ±100meV or below.

The QTNM Project (pg. 16)

- The ultimate goal is to develop an experimental apparatus with such a sensitivity and high energy resolution that is needed for **measuring neutrino mass down to ~10 meV** that is set by observations of neutrino oscillations.
- In neutrino mass measurements, the sensitivity of an atomic tritium CRES measurement of m_β is often expressed in terms of the standard deviation on the fitted value of $m_\beta{}^2$.
    - This gives the minimum detectable neutrino mass that the experiment is sensitive to at 90% confidence.
- What affects the sensitivity is the precision with which the cyclotron frequency can be determined, and the accuracy with which the magnetic field can be mapped and corrected for.
- We come back to the fact that the observation time is crucial because the longer you observe the electron's radiation, the more precisely you can measure the frequency, which translated to better energy resolution and better neutrino mass sensitivity.
    - There are some statistical bounds on this precision that are dependent on the observation time (which gives the minimum uncertainty) and the inverse observation time (which gives the maximum usable observation time before the electron is lost. These two bounds define the energy resolution window of the experiment.

Plot: (pg. 17)

- The plot shows the estimated sensitivities of a CRES experiment to measure mß depending on the tritium atom number density in the measurement volume.
- The set of volumes considered are shown with a range from 10^{-3} to $10\ m^3$ and the magnetic field strength is B=1T in all cases. For each of these there's also a **measurement-campaign duration** of 1 to 10 years.
- All the coloured bands all bounded by two curves. They represent the range of sensitivities that are expected by the frequency precision measurement limit set by the observational time (the continuous curve) and the limit set by the inverse observational time which is the dashed-dotted curve.
- Horizontal lines denote the current and the projected limit of KATRIN experiment with tritium molecules, and the minimally allowed value of mß IO neutrinos.
- At low number densities the sensitivity on the effective mass is limited by the ß-decay-electron count rate. As the tritium atom number density increases from 10^8 up to $10^{11}\ cm^{-3}$, the sensitivity increases because of the increase in ß-decay events.
- In this regime, the precision with which the cyclotron frequency can be recovered according to the limit by observation time bound offers a higher sensitivity to the effective mass for any given atom number density, compared to the precision set by the inverse observation time.
- For densities above $10^{13}\ cm^{-3}$, the scattering rate tightly restricts and leads to a reduction of the achievable sensitivity.
- The three upper curves (green, purple and orange) are the results of calculations in which the relative uncertainty in the strength of the magnetic field experienced by the radiating electrons is 10^{-6} meaning that the uncertainty is 1μT because B=1T.
- We can see that the green curve would not result in a sensitivity on the effective mass below the current limit set by the KATRIN experiment in their work with tritium molecules, but it if the measurement volume is increased to 0.05 m^3 it will provide a better measurement sensitivity than the final limit projected for KATRIN (dashed line).
- If the CRES measurement volume is increased to 10 m^3 in an ultimate large scale facility, the sensitivity on the effective mass will no longer be limited by the count rate or cyclotron radiation observation time, but it will be dominated by the accuracy with which the magnetic field experienced by each ß-decay electron is

known. If the magnetic field is characterised with an accuracy of 10^{-6} and a 10-year-long measurement campaign is undertaken, the lower bound on the achievable sensitivity approaches **100meV**. Here this sensitivity is not expected to be strongly dependent on the T atom number density within the range from 10^{11} to $10^{13} cm^{-3}$, and would be an improvement on the projected final limit of the KATRIN experiment. And it would also bring a CRES experiment with T atoms into a regime where the sensitivity to the effective mass begins to surpass the 100meV limit that is set by experiments with tritium molecules that arise from the uncertainties in the internal molecular rotational and vibrational state distributions after ß decay. However it does not allow access to the minimal value of IO neutrino effective masses expected.

- To enhance the sensitivity of T-atom CRES experiment toward values of mß in this range and below, it is necessary to improve the magnetic field characterisation, which remains a challenge with an instrumented volume of 10 m^3 . But if an improvement of the 10^{-7} can be achieved, then the sensitivity toward these values can become accessible.
- For the case of NO, the improvement of the sensitivity toward the ~10meV lower bound on the mß will be dominated by the requirement to significantly increase the instrumented volume with a smaller increase in magnetic field accuracy.

The general goals of QTNM project are as follows: (pg. 18)

1. Development of high phase-space density, low kinetic energy sources of T atoms; implementation of methods to efficiently filter, confine and transport these atoms to the CRES measurement region.
2. Realisation of a scalable approach to the construction of a CRES spectrometer that could, in longer terms, be implemented in a large-scale facility to achieve a total instrumented volume ~10 m^3.
3. Exploiting atomic quantum sensors for high-precision minimally-invasive magnetic field mapping within the instrumented region of the CRES spectrometer
4. Development of a multichannel antenna or a cavity-based approach to collecting the cyclotron radiation with high efficiency and low background noise
5. Development of scalable multichannel quantum-noise-limited cryogenic microwave receivers that maximise the ratio of the cyclotron radiation signal

from ß-decay-electrons to the background and amplifier noise, allowing precise microwave frequency metrology.

The general approach that is followed by QTNM project is shown schematically in this figure: (pg. 19)

- The main elements of this scheme are a high phase-space density source of T atoms (I) produced by the dissociation of tritium molecules in an electric discharge. So you want to have many T atoms, packed into a small volume and with low velocities so that they are easy to control. A dense, cold source increases the event rate and measurement precision.
- The T atoms are then transported to the CRES region (II) as a magnetically guided beam (you don't want the atoms to randomly float around). In CRES measurement region, which is the electron spectrometer is kept at a low temperature of 4K, and a uniform magnetic field is applied throughout this region using superconducting magnets, in order to get the cyclotron frequency of the electrons and the energy.
- To calibrate and monitor the magnetic and electric fields, this project uses atoms in high Rydberg states as quantum sensors, that can operate directly inside the cold apparatus, using either tritium or other non-contaminating atoms.
- Electrons generated by T atoms that undergo ß-decay in the measurement region, are detected by measuring the microwave radiation emitted as they experience the cyclotron motion in the magnetic field.
- This radiation is collected by an ultra-low-noise receiver which is a microwave detector, using purpose-developed quantum-noise-limited amplifiers, that add almost no thermal or electronic noise to the signal, which is crucial because the signal from a single electron is very weak.
- The receiver is shaped and tuned to optimally absorb the specific EM field pattern of the cyclotron radiation, to ensure maximum sensitivity and clean detection of the electron's frequency. Then the last step is the digitisation.

This is a large-scale experimental apparatus that must ultimately be constructed, so all these individual components are being developed, tested and refined sequentially.

With a working volume on the order of 10 m^3 which is required to be sensitive to values of mß below 100meV, is expected to require international collaboration.

Storage Ring: (pg. 21)

- This diagram summarises how tritium is produced, manipulated and sent to the CRES measurement region. The idea is to confine the T atoms in a circular magnetic guide so that they can circulate repeatedly through the CRES detection regions, be observed for a longer time and enable a scalable design for such a large-scale experiment.
- **1**: Here we have the atomic tritium source. Molecular tritium is dissociated into atoms via an electric discharge. The whole source is kept a low temperature, ~4K, to prevent atoms from recombining, keep them at low energies so that it's better to control them and to minimise background gas.
- **2**: Laser spectroscopy is used to characterise the beam, determine its density, temperature, velocity and so on, and more to tune and optimise the beam before injection.
- **3**: Atomic tritium has an unpaired electron, so it has a magnetic moment and can interact with a magnetic field. Also, the T atoms get deflected while the tritium molecules barely move, so this allows them to be spatially separated in the beam because the molecules can interfere with atoms reducing signal quality and increasing atomic loss.
- **4**: The selected atomic tritium beam will be injected into the storage ring using an arrangement of permanent magnets to generate an inhomogeneous magnetic field so that it guides and focuses the atoms depending on their spin state, acting as a beam combiner so that you get a well-aligned beam entering the storage ring.
- **5**: The storage ring is where the atoms circulate. It has to 180° curved sections, each containing 60 permanent magnets for guiding and storing atoms in a loop.
- **6**: The second atomic beam characterisation measures the state of the atoms after circulating in the ring. It helps to assess losses, spin flips or recombination after multiple passes. It's useful for improving trapping efficiency.
- **7**: Then a modular CRES detection region comprising of superconducting solenoid magnetic to generate strong uniform magnetic fields and microwave receivers. Magnetic lenses and guides are required to transport and collimate the atomic beam between the curved sections of the ring to the CRES region.
- To scale the apparatus to allow the ß-decay spectrum of larger quantities of T atoms to be recorded, and increase the count rate close to the endpoint, the separation between the 180° curved sections of the ring can be increased so that

multiple equivalent CRES modules can be installed in the straight sections on each side.

- Increasing the length of the individual CRES regions by a factor of 2 while maintaining an inner diameter of ~10cm, would allow total instrumented volumes on the order of 10 m^3 to be achieved with 640 modules arranged in multiple parallel beam lines or storage rings.

Development of quantum-noise-temperature limited amplifiers

(pg. 26)

- The collaboration has investigated detection methods for the electron's cyclotron radiation across a range of magnetic fields between 0.5T - 1T.
- The current focus is on a magnetic field of ~0.7T resulting in observing frequency of 18GHz.
- Therefore, a multi-channel readout system featuring sizeable arrays of microwave receivers operating near the quantum noise limit is needed.
    - Quantum noise is the irreducible noise introduced due to the uncertainty principle: according to the uncertainty principle, you can't measure a signal's amplitude and phase simultaneously. This limits how precisely you can amplify or measure EM, and especially microwave radiation.
    - The quantum noise limit is the minimum amount of noise that any amplifier must add when measuring a signal, because of quantum mechanics.
- The QTNM project has been developing two types of superconducting amplifiers with added-noise close to the Standard Quantum Limit: SPKs and SLUGs.

SPKA (Superconducting Parametric Kinetic-Inductance Amplifiers

(pg. 27)

- Quantum technologies are facing challenges when it comes to extraction and amplification of weak quantum signals, especially for those operating in cryogenic environments.
- These amplifiers play a crucial role in the preparation and readout of quantum states at microwave frequencies, enabling high-fidelity measurements of superconducting qubits.

- These amplifiers have demonstrated high gain 10-30 dB while maintaining minimal added noise and maximising SNR, while operating at GHz frequencies.
- While large gain is desirable, it comes with the cost of additional added noise. Generally the signal quality is quantified by considering the SNR. Here they define the SNR improvement as the difference between the SNR when the amplifier is on and off.
- This plot shows the signal gain (left y-axis) and the SNR improvement (right y-axis) versus the pump power in dBm. Pump power is the microwave power used to drive the amplifier's nonlinear element. The values are negative because this is a logarithmic unit of power referenced to 1mW. The low powers are enough to drive the amplifier and also not to cause any damage to it.
- **GAIN**: As the pump power increases, the gain increases and it peaks around -1.3 dBm at ~20dB signal gain. Beyond that point the gain drops possibly due to instability of the amplifier because of the increase of the pump power. The gain curve starts at 5 dB simply because the pump is already delivering enough power to amplify the signal slightly.
- **SNR**: This curve shows how much better the amplifier is making the SNR compared to no amplification. The maximum of SNR improvement is around ~7dB and it corresponds to ~15dB signal gain, so it happens before the signal gain reaches its maximum value, so the peaks do not coincide. This happens because they slightly compress the amplifier at room temperature when maximal gain is being approached, which leads to a shift between the point of maximal gain with respect to the point of maximal SNR improvement. This curve starts at a higher pump power because at lower pump power the gain is too small to improve the SNR. Even though there's some gain, it's not enough to overcome the noise added by the amplifier itself for example. So the improvement becomes meaningful after a certain threshold gain.

SQUID and SLUG (extra, removed from the presentation)

- Alternative is to use SQUID which offers robust fabrication, a good dynamic range, compactness and helps to minimise the space it occupies within a cryostat.
- Superconducting properties allow for very low intrinsic noise, however its operation is limited to hundred of MHz.

- Because of the frequency limits of SQUID amplifiers, the collaboration is developing a different variant of SQUID called SLUG which allows operation at frequencies of several GHz.
- With SLUGs it is possible to achieve a gain of 20dB and noise within a factor of 4 of the standard quantum limit at a frequency of 18GHz.
- The plot shows the results of a simulation of a SLUG amplifier with input circuit designed to operate at 18GHz. Due to a difference in the optimal input impedance for gain and noise, the frequency of maximum gain and the frequency of minimum noise are not the same.