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Upgrades at the TITAN Penning Trap for Tests of the Standard Model

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Discovery, accelerated

Outline

1. **Why are mass measurements important?**
2. **The TITAN facility and its Penning trap**
3. **Challenges brought on by contaminants and poor vacuum**
4. **Redesigning the TITAN Penning trap to remove the contaminants**
5. **The outlook of Penning trap mass spectrometry at TITAN**

Why are mass measurements important?

- **A fundamental characteristic of the atom is its mass and is the result of all the atomic and nuclear interactions.**
- **It is an amazing tool to probe many characteristics of the nucleus.**
- **Various degrees of precision (Δm/m) are required for mass measurements:**

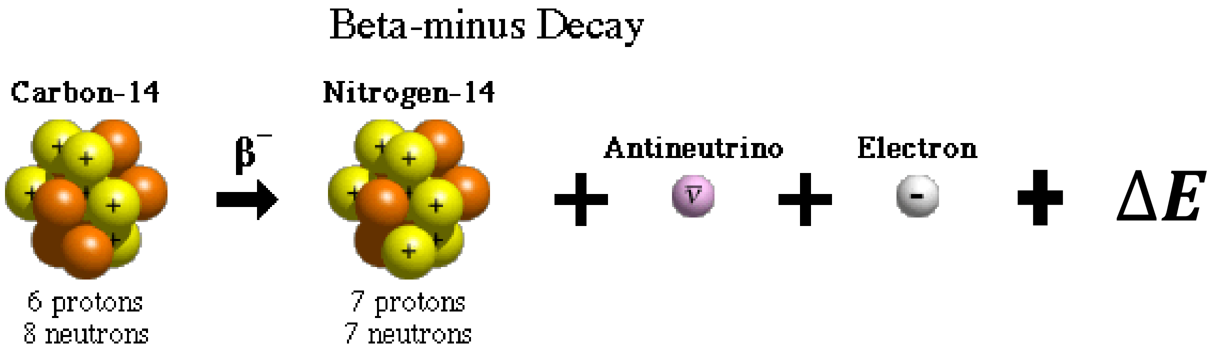
Nuclear structure: 10^{-6}

Nuclear astrophysics: 10^{-7}

Fundamental symmetries: 10^{-9}

- **The only way we can achieve a precision of 10^{-9} is through Penning trap mass spectrometry.**

Tests of fundamental symmetries

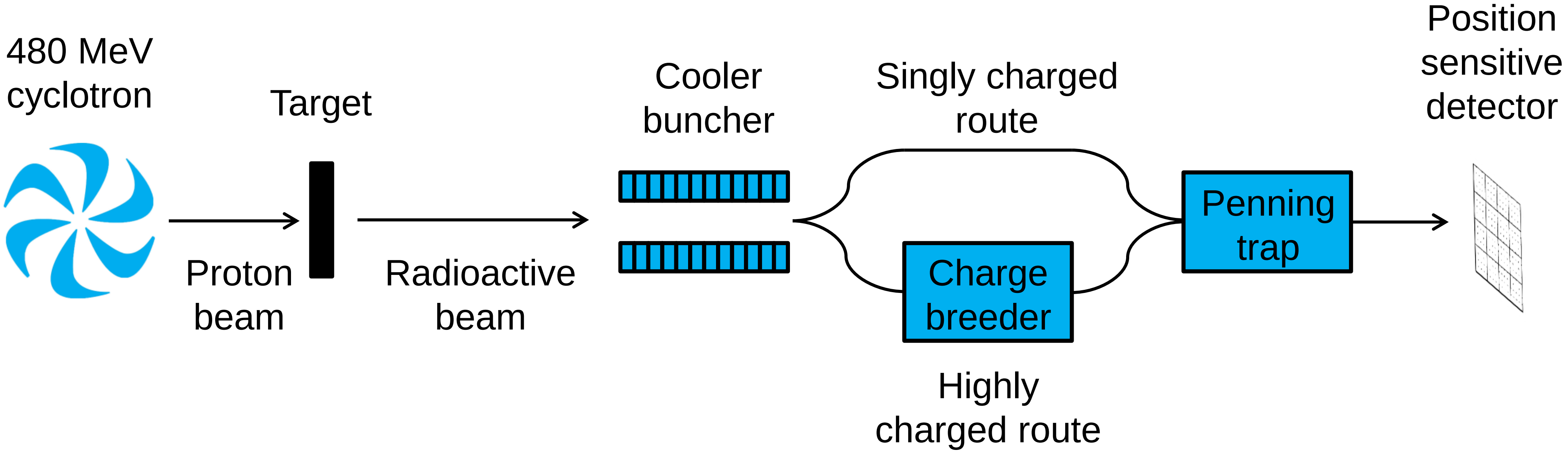


- A theoretically predicted decay process in the Standard model is neutrinoless double beta decay. Searches for which address questions such as the nature of the neutrino and the absolute neutrino mass scale.

- Precise Q-value measurements are essential to theoretically determine the half-life of each possible decay mode.

- Penning trap mass spectrometry is used to obtain precise Q-value measurements.

The TITAN facility

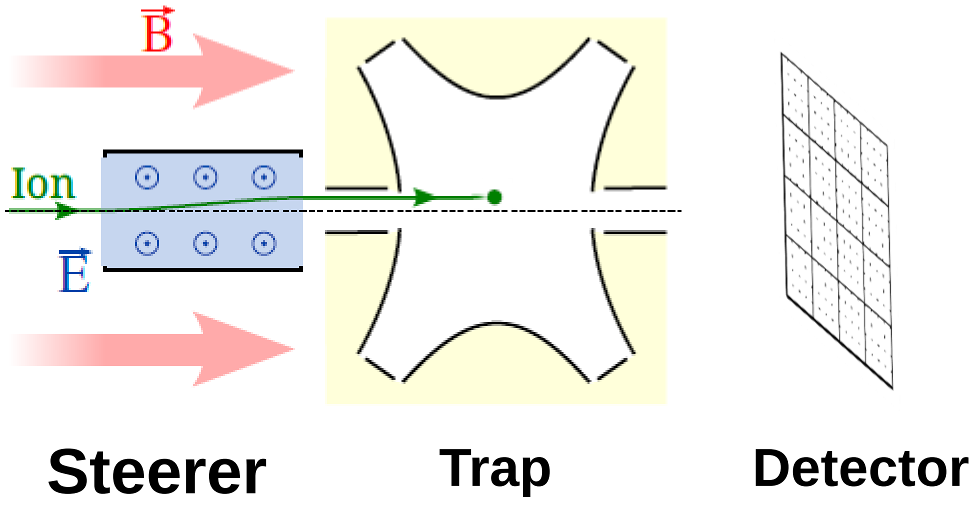


- **Achieved a precision of 10^{-9} for mass measurements.**
- **Set the records for shortest lived nucleus measured with a Penning trap at 8 ms for ^{11}Li and also the most exotic nuclei (N/Z=3) for ^{8}He.**
- **Pioneered the use of highly charge ions in Penning trap mass spectrometry with the measurement of ^{74}Rb in a 8-12+ charge state.**

The TITAN Penning trap

- **The TITAN Penning trap is a hyperbolic Penning trap with a 3.7 T magnetic field**

- **Ions are given cyclotron motion and the frequency is determined by using a frequency scanning method that measures the time of flight between the trap and a detector.**



$$m = \frac{qB}{2\pi \upsilon_c}$$

$$\Delta m = \frac{1.6 \cdot \pi \cdot m}{q \cdot B \cdot T_{RF} \cdot \sqrt{N_{ions}}}$$

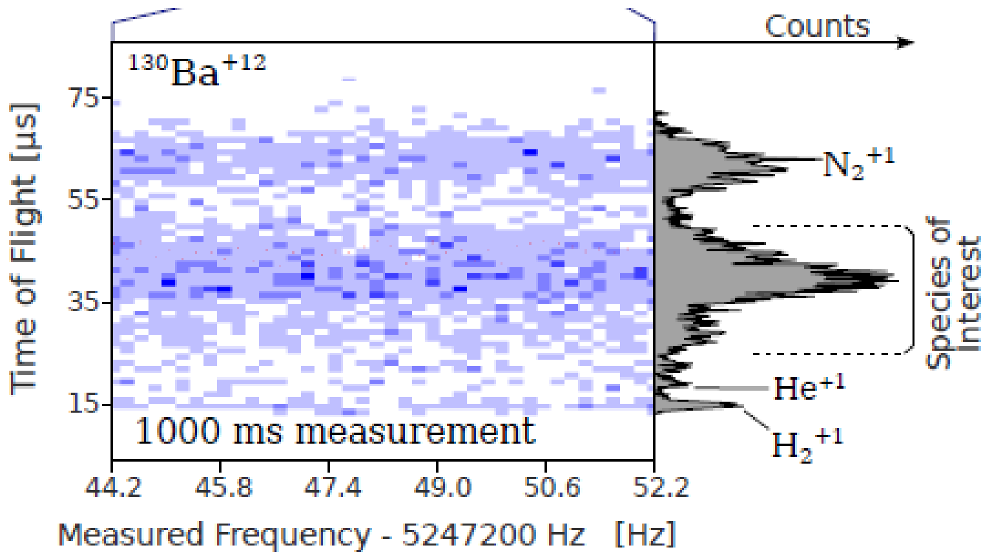
- **Our ability to access highly charged ions enables use to significantly reduce the error on the mass.**

Contaminants within the TITAN Penning trap

- **Contaminants present within the TITAN Penning trap are often ionized by the high charged ions, thus losing their highly charged nature.**

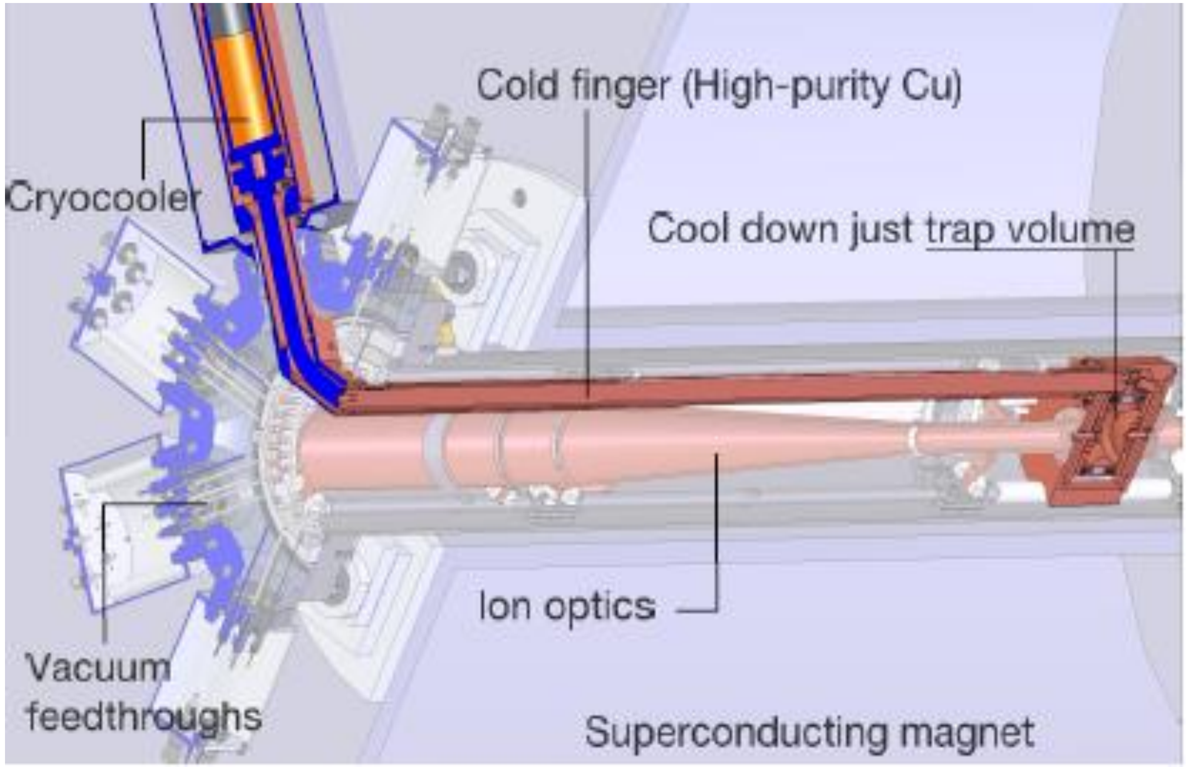
- **These ionized contaminants will also slightly change the measured cyclotron frequency of the measurement ion.**

- **This is why we need an amazing vacuum!!**



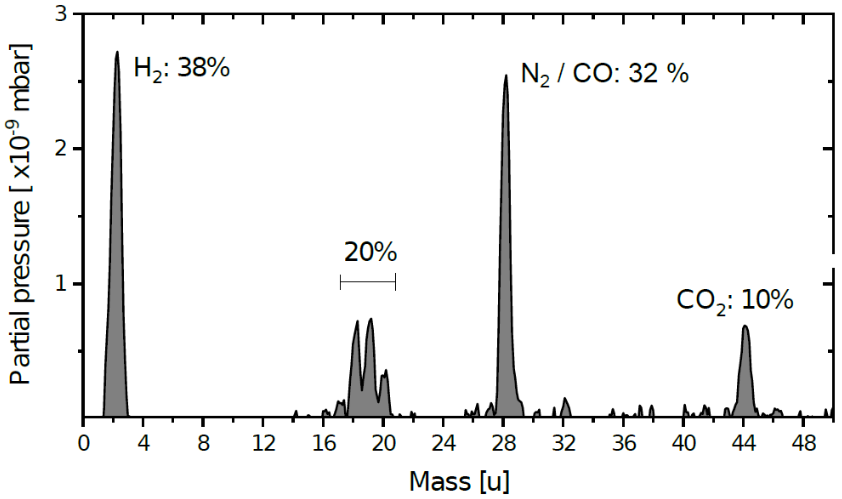
The TITAN Penning trap has gone cryogenic!

- **A cryocooler cools a high purity copper finger that extends to the trapping volume.**
- **The trapping region of the Penning trap is now cooled to 24K.**



The cryogenic Penning trap

- **The trap itself has also had a redesign. It now has a copper shield to further insulate the trap from the outside environment.**
- **A ceramic support structure.**
- **A coconut based carbon getter.**



- **It has now reached a pressure on the order of 10^{-11} mbar.**

Commissioning of cryogenic Penning trap

- **In September 2023, we conducted our first experiment measuring the $^{48}Ca > {}^{48}Sc$ Q-value. This was to measure the feasibility of detecting single beta decay in future experiments.**

- **Online analysis showed the error on this measurement to be in the region of 1.2 keV down from the current 5 keV.**

- **This gives us a precision of $2.7*10^{-8}$ for MPET.**

Summary and outlook

- **We have successfully commissioned the cryogenic Penning trap and reached a precision of close to 10^{-9}.**

- **We have reached the desired pressure of 10^{-11} mbar within the Penning trap to enable us to measure highly charged ions without significant charge exchange.**

- **We are starting to implement a phase dependent method for cyclotron frequency determination. This will be five times more precise than our current method.**

- **We will be on cusp of achieving 10^{-10} precision once we can use highly charges ions with our phase dependent method.**

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Thank you
Merci

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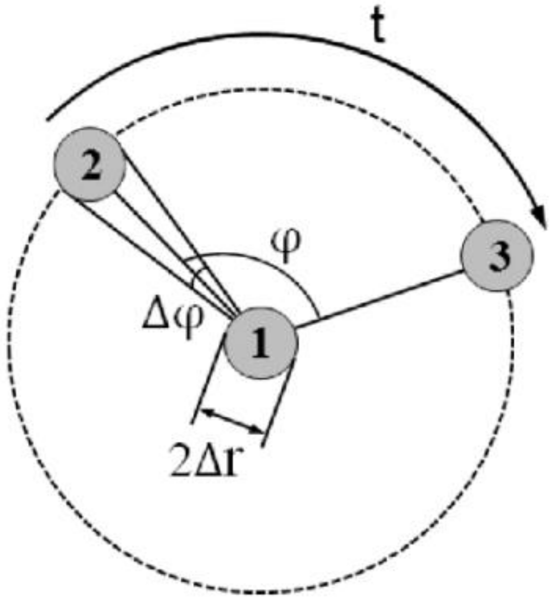
The phase dependent method (PI-ICR)

- **Ions are inserted into the Penning trap off axis and left for a period of time for their cyclotron motion to carry them around the trap.**

- **The traced angle over time, t is then related to the cyclotron frequency.**

- **This is 5 times as precise as our current time of flight based method.**



$$\nu_c = \frac{\phi + 2\pi \cdot n}{2\pi t}$$

$$m = \frac{qB}{2\pi\nu_c}$$