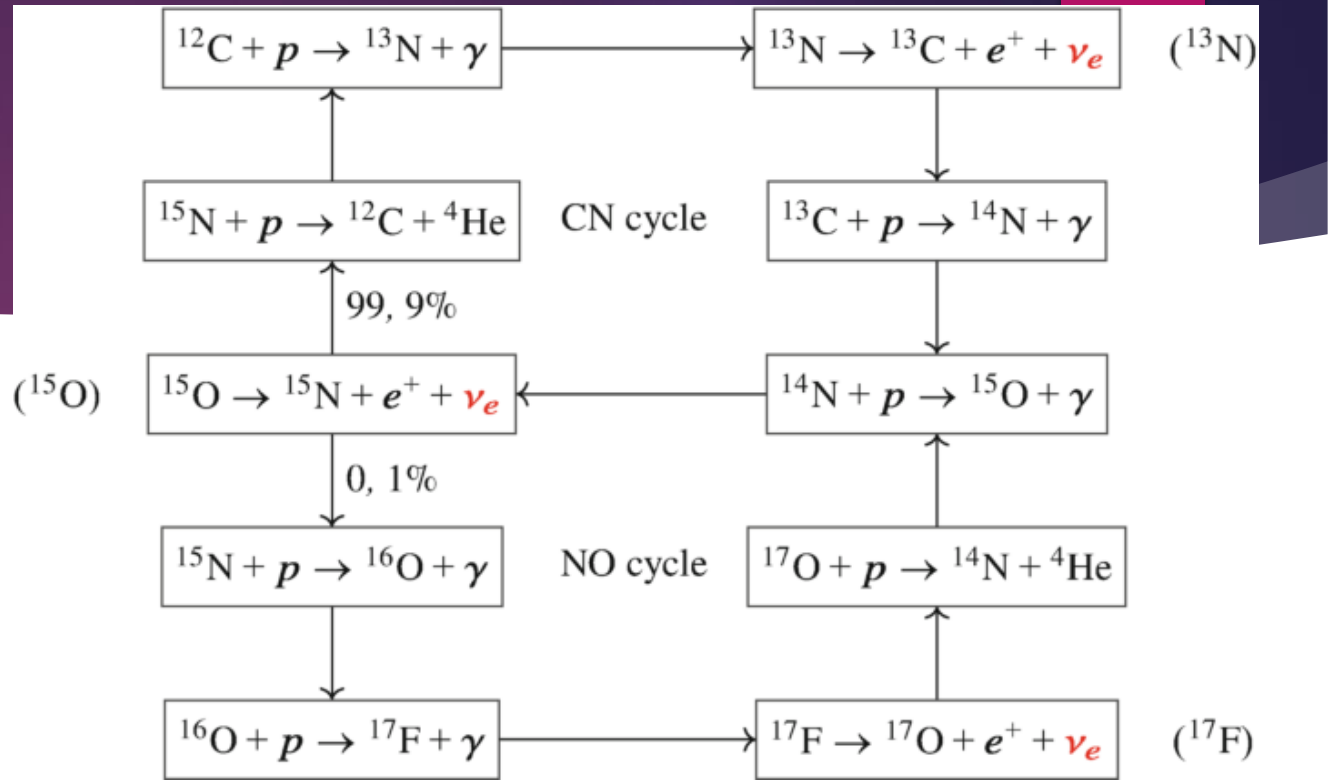
# Measurement of the $^{14}N$ (p, γ) $^{15}O$ Reaction Cross Section Using Inverse Kinematics

GÁBOR BIHARI

WITH THE SUPERVISION OF TAMÁS SZÜCS

# The CNO cycle

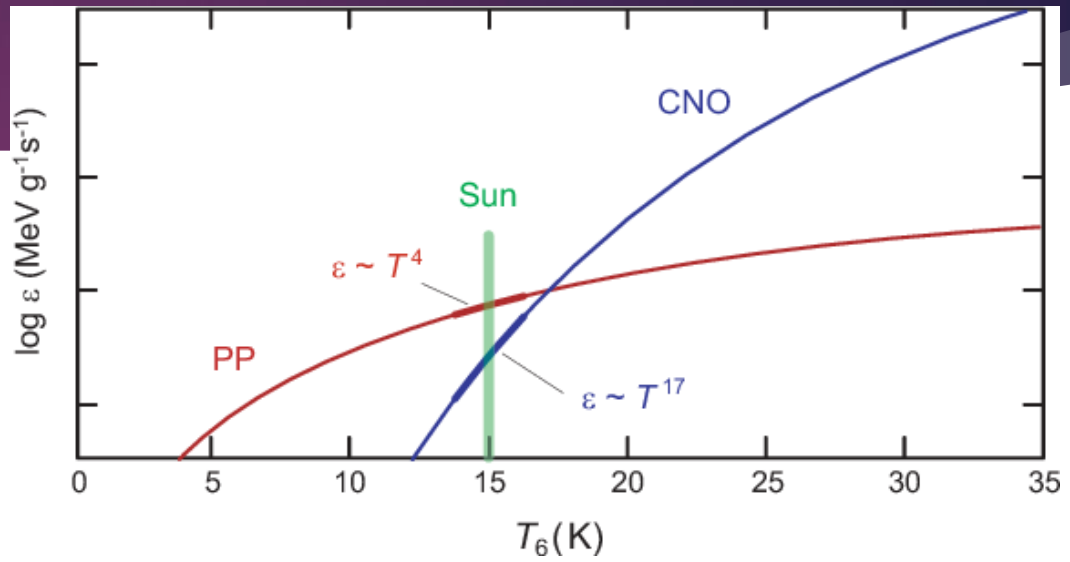
- **Core Definition:** A catalytic nuclear fusion process that converts hydrogen into helium in stellar cores.
- **Key Elements:** Uses **Carbon (C), Nitrogen (N), and Oxygen (O)** as catalysts to facilitate the reaction.
- **Energy Output:** Releases energy primarily through positron emission and neutrino release alongside gamma-ray photons.
- **Discovery:** Independently proposed by physicists **Carl Friedrich von Weizsäcker** and **Hans Bethe** in the late 1930s.

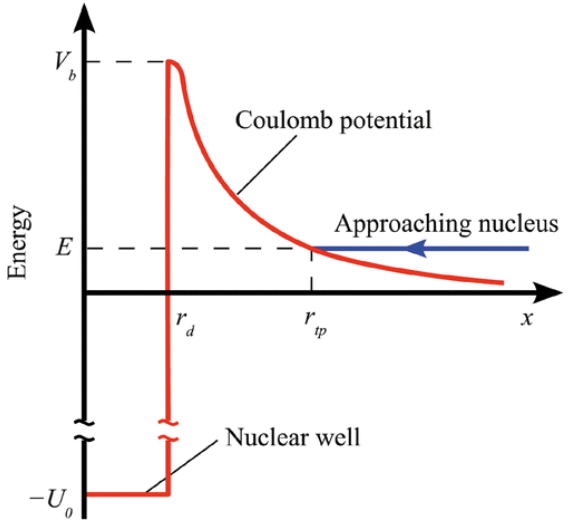


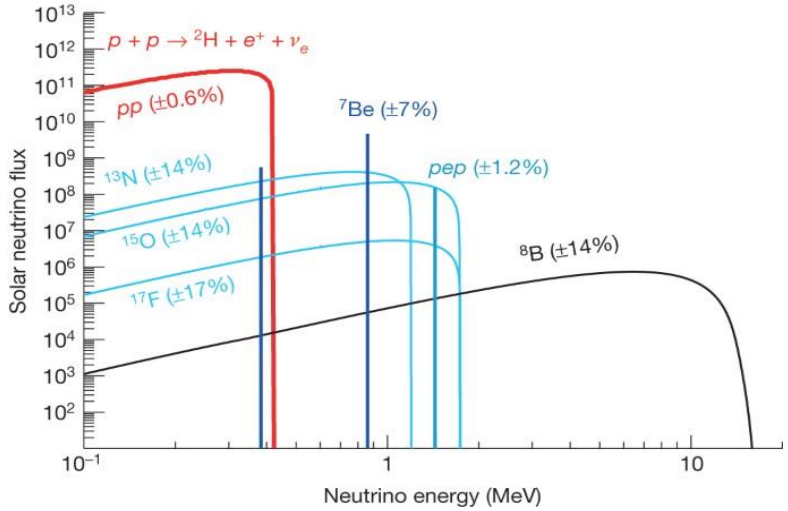

During hydrogen burning via the CNO cycle, the initial abundances of carbon, nitrogen, and oxygen are redistributed until they reach a specific equilibrium ratio dictated entirely by the reaction rates of the cycle itself. As a result, the final proportions of these catalytic elements become completely independent of their original abundance levels in the stellar core.

# CNO dominance in massive stars

- **Mass Threshold:** Becomes the dominant energy source in stars with masses **greater than 1.3 Solar Masses ($M_s$)**.
- **Temperature Sensitivity:** Highly sensitive to temperature ( ~ $T^{16}$ or higher), making it extremely efficient in hotter, massive cores.
- **The 1.3 $M_s$ Turning Point:**
  - *Below 1.3 $M_s$ (e.g., our Sun):* The Proton-Proton (p-p) chain dominates.
  - *Above 1.3 $M_s$:* The CNO cycle rapidly takes over as the primary fusion mechanism.
- **Stellar Impact:** Drives convective cores and leads to much higher luminosities in massive stars.

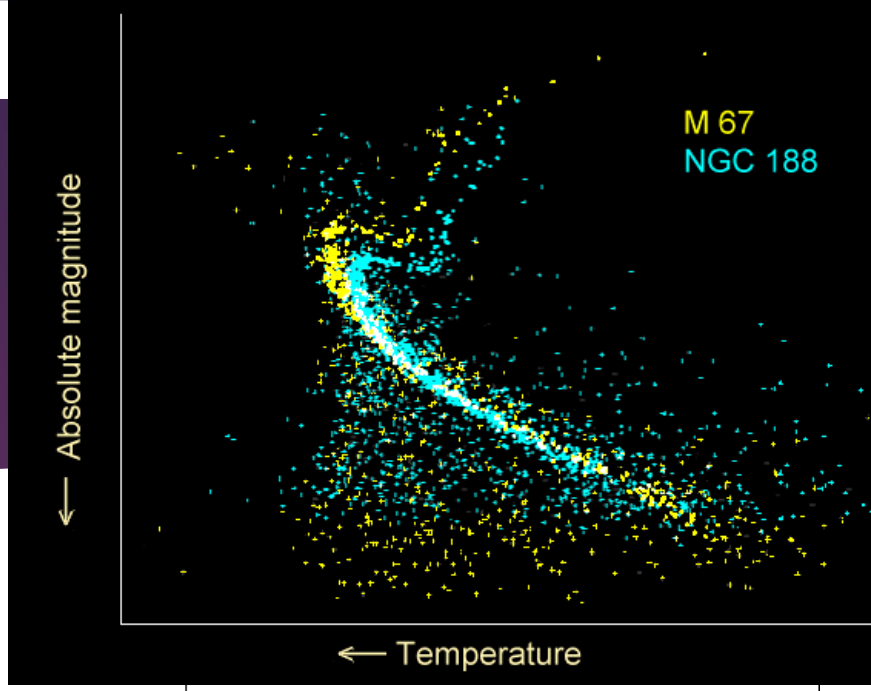


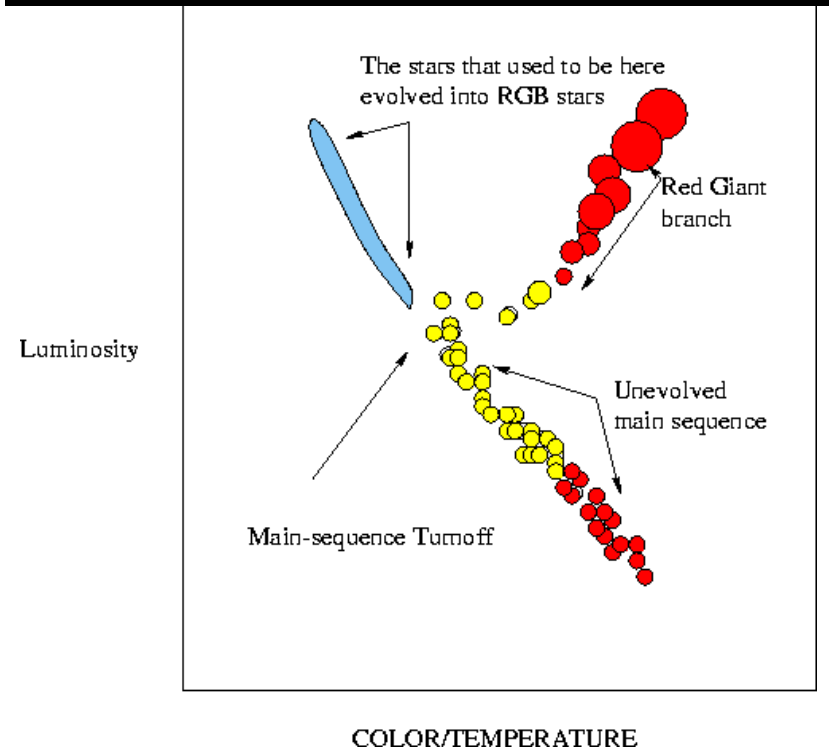



# The $^{14}N(p,\gamma)^{15}O$ Bottleneck Reaction and Its Cosmological Impact

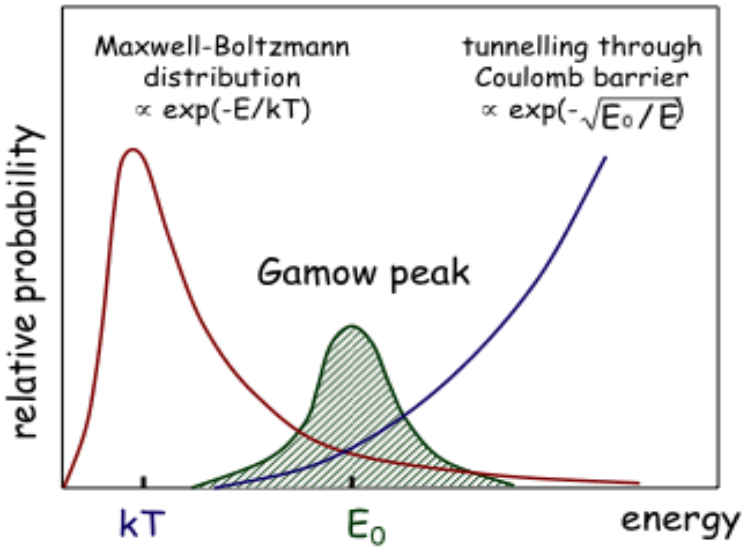
- **The Main Bottleneck:** The  reaction has the smallest cross-section in the cycle, making it the slowest step that regulates the overall CNO energy production rate.
- **Stellar Lifetimes:** Because it determines the rate of hydrogen burning, the precision of this specific cross-section directly dictates the lifetime of massive main-sequence stars.
- **The Globular Cluster Connection:**
  - Controls the luminosity at the **Main Sequence Turn-Off (MSTO)** point on the Hertzsprung-Russell (HR) diagram.
  - The MSTO of the oldest **globular clusters** serves as a vital indicator for when these ancient stellar groups began to evolve off the main sequence (finished hydrogen burning).
- **Measuring the Age of the Universe:**
  - By pinning down the exact rate of this reaction, astrophysicists can calculate the precise age of the oldest star clusters.
  - This provides a critical, independent lower limit for the **absolute age of the Universe**.

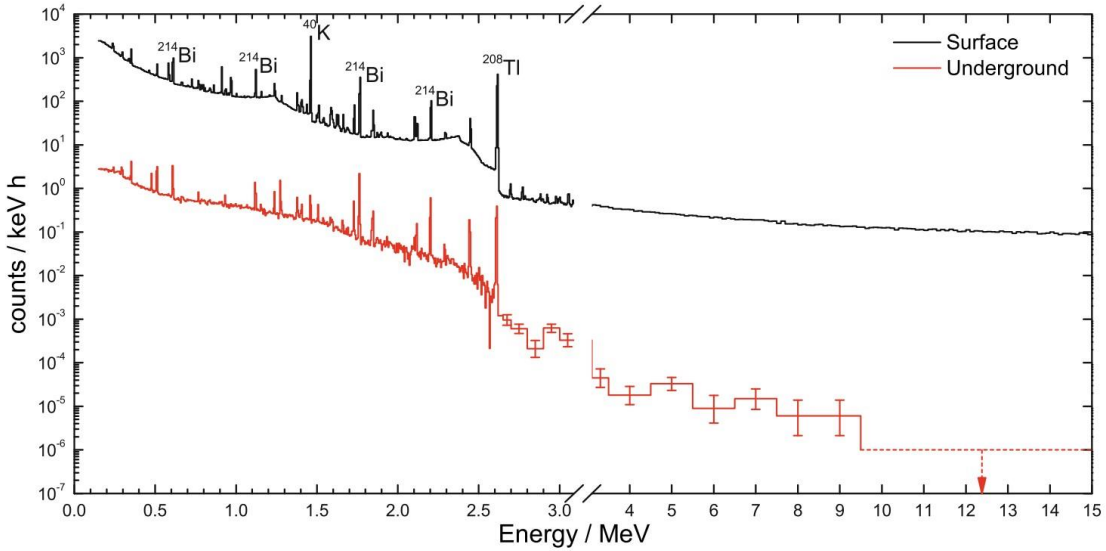




# Overcoming the Experimental Challenge: Deep Underground Laboratories



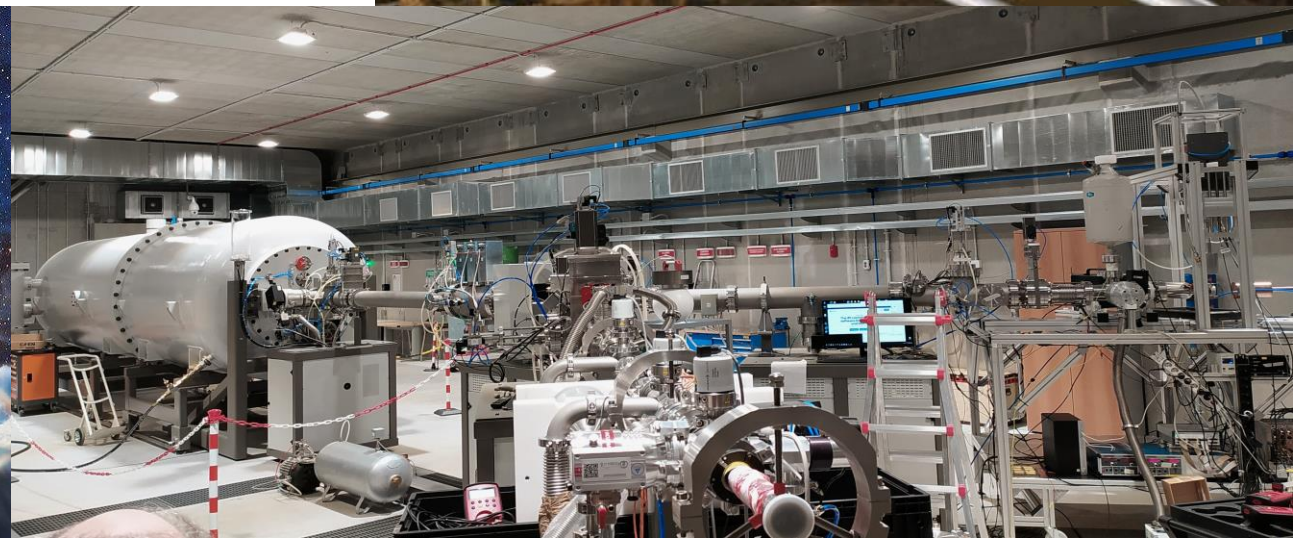

- **The Low-Energy Barrier:** At stellar energies (the Gamow peak), the $^{14}N(p,\gamma)^{15}O$ reaction cross-section drops exponentially, making the reaction rate incredibly small.
- **The Surface Noise Problem:** On Earth's surface, cosmic ray-induced background radiation completely drowns out the weak γ-ray signals emitted by this reaction.
- **The Deep Underground Solution:** Measurements must take place deep underground, where kilometers of solid rock act as a natural shield to filter out cosmic-ray muons. To suppress the remaining low-energy gamma background originating from the surrounding rock walls, thick lead shielding is placed around the experimental setup.

# Pioneering Facilities:

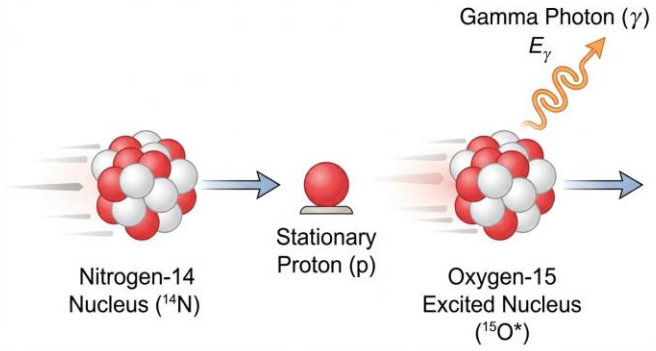



- **LUNA (Laboratory for Underground Nuclear Astrophysics):** Located under the **Gran Sasso** mountain in Italy. It pioneered the first direct low-energy measurements of this bottleneck reaction.
- **JUNA (Jinping Underground Nuclear Astrophysics):** Located in the ultra-deep **China Jinping Underground Laboratory (CJPL)**, providing even lower background environments for high-precision nuclear astrophysics.

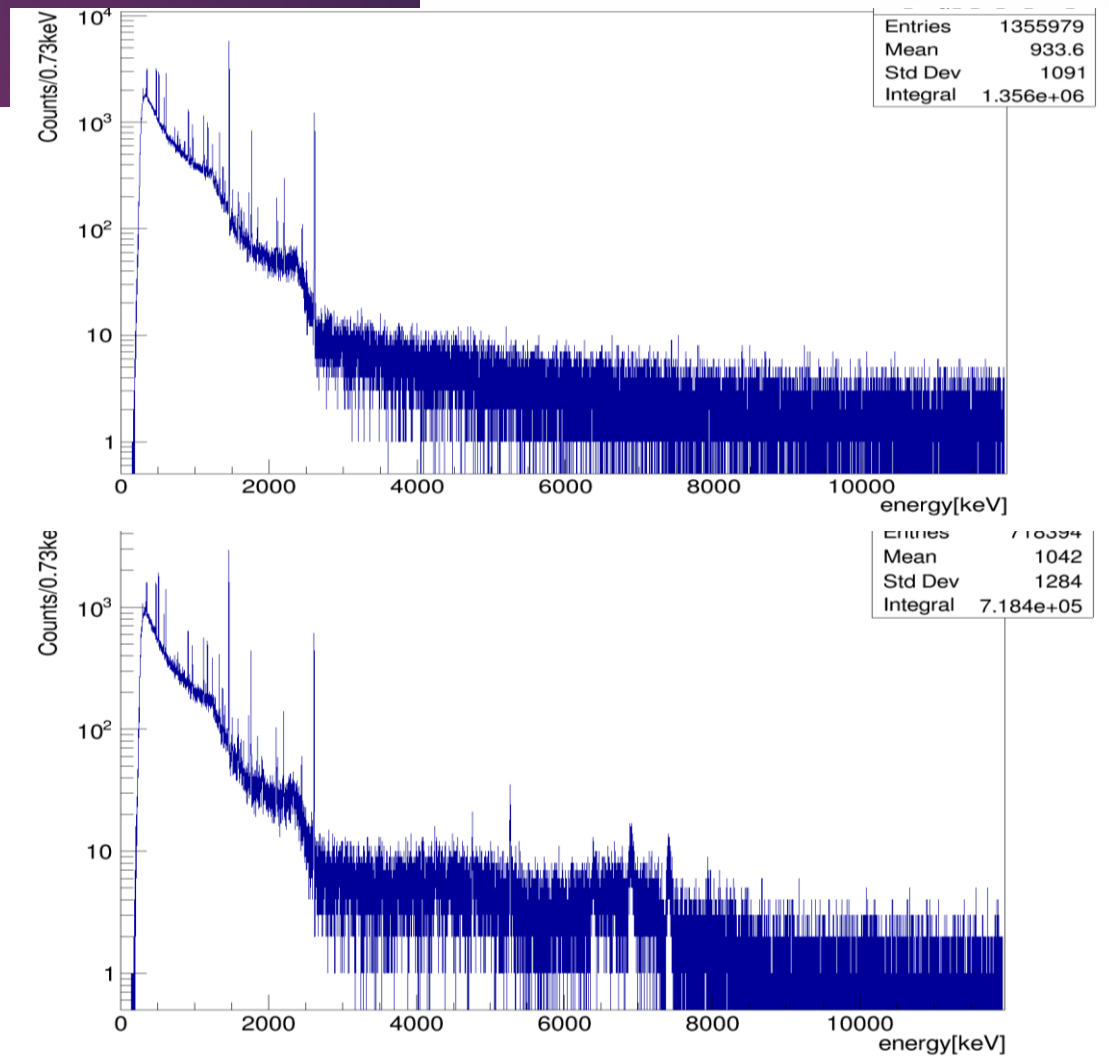


# An Alternative Approach: Inverse Reaction Kinematics

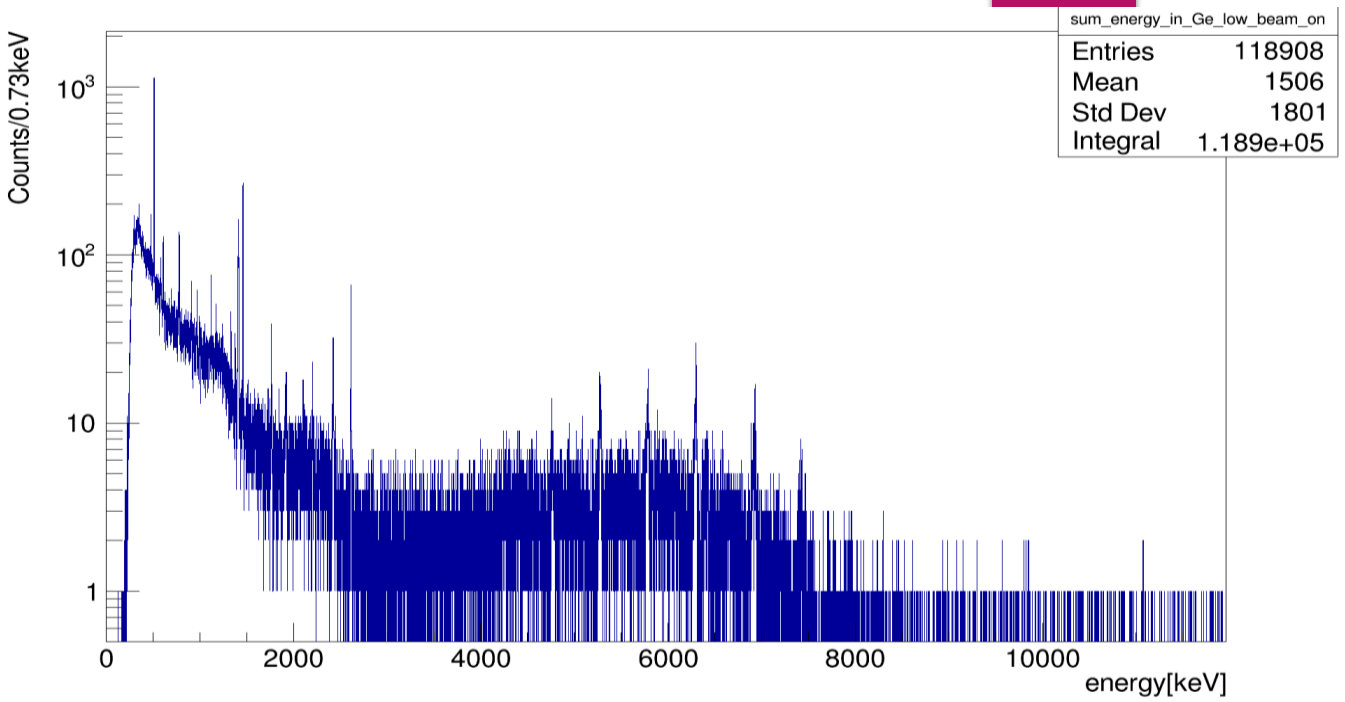


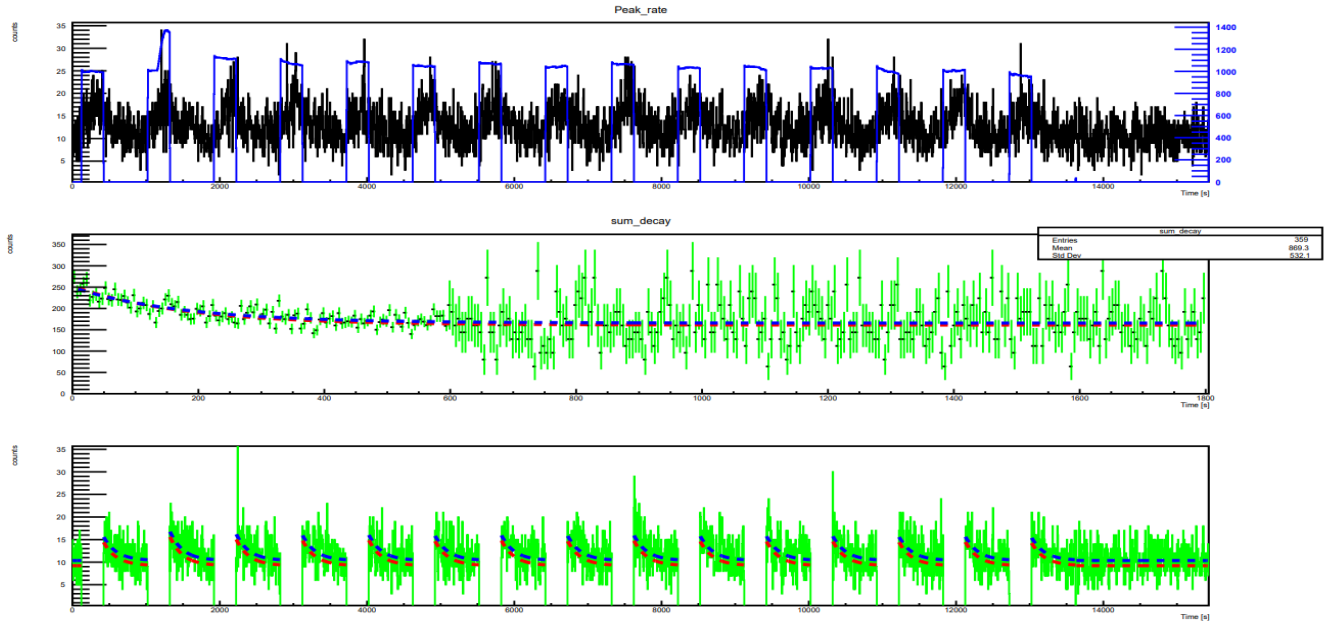

- **The Experimental Setup:** Instead of firing protons at a nitrogen target, the setup is inverted by bombarding a **hydrogen target** with a beam of **$^{14}$N ions**.
- **Eliminating Activation:** Traditional high-energy proton beams often activate surrounding materials, creating an unwanted radioactive background that obscures the weak measurement signals. At these low energies (a few MeV), the heavy $^{14}$N ions lack the energy required to induce nuclear reactions on any surrounding materials or impurities.
- **Target Selectivity:** Because of this energy threshold, the nitrogen ions can only interact and undergo fusion with the hydrogen nuclei in the target, ensuring a much cleaner signal.
- **Beam induced background:** Due to deuterium impurities in the target, the $^{14}$N(d,pγ)$^{15}$N reaction still creates an observable background, which can be detected clearly at lower beam energies (at 252 keV CME – the deuterium lines are wider due to the recoil of the $^{15}$N nucleus).



# Measurement on thick targets

- **The main reaction:** At slightly higher energy (269 keV CME) the prompt gamma spectrum of the $^{14}N(p,\gamma)^{15}O$ reaction clearly appears, proving the viability of our experimental method.
- **The spectrum:** The main lines of excited $^{15}O$ (6,79 and 7,55 MeV) appear at 6,95 MeV and 7,73 MeV due to the Doppler-shift. The single and double escape peaks are also clearly visible.
- **Sawtooth activation curve:** During the on-bean accumulation of the reaction products, we can observe the continuous rise of the 511 keV annihilation peak, while switching off the beam causes exponential decay of the source.
- **Half-life verification:** The analysis of the activation curve proves that the source of the 511 keV gamma energy is the 122 sec half-lived $^{15}O$, while at the same time it gives independent data for the reaction yield and thus, the cross section.



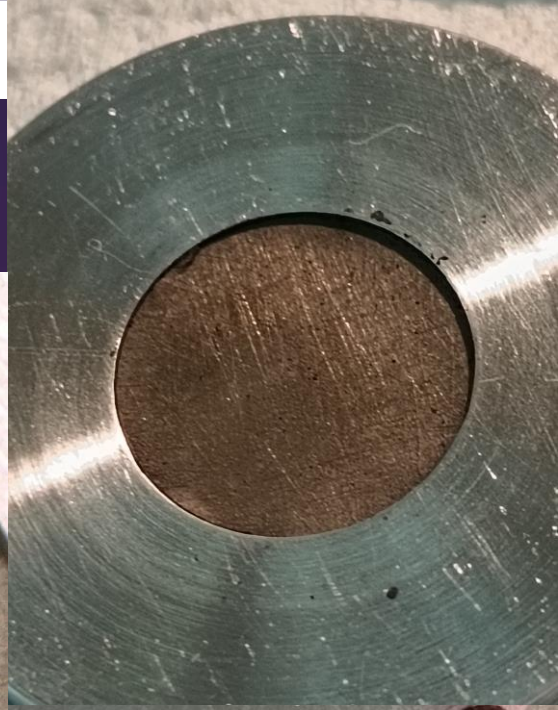



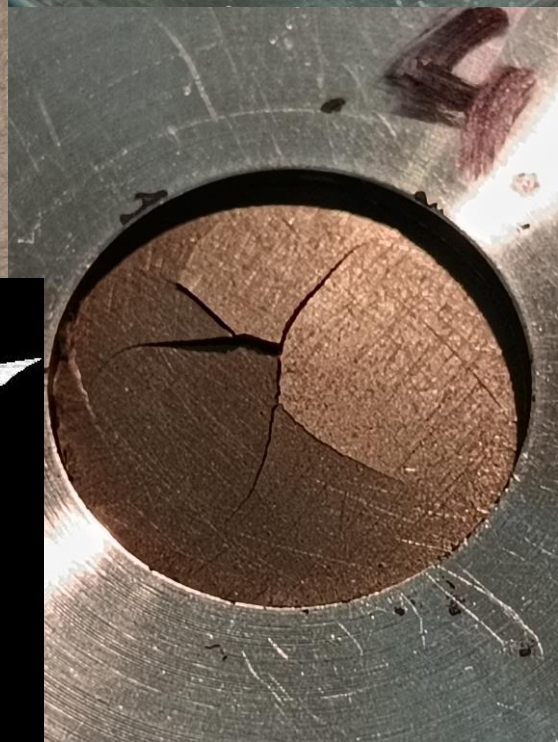
# Thick Target Fabrication & Thermal Challenges

- **The Method:** Titanium Hydride ($TiH_2$) powder was pressed into a 1 cm diameter cavity milled into an aluminum backing disk.
- **Mechanical Failure:** While the powder consolidated, the elastic spring-back of the aluminum substrate caused several pellets to crack.
- **Thermal Contact Issue:** Significant hydrogen leakage was observed during beam irradiation, revealing poor heat dissipation to the water-cooled backing.
- **The Lead Lining Solution:** We are now testing a lead (Pb) lining inside the cavity. When reaching 120 bar pressure, the lead "flows" to bridge the gap and ensure a reliable thermal and structural bond.







# Thin Target Fabrication via Plasma Sputtering

- **The Process:** Sputtering pure titanium in a mixed argon-hydrogen atmosphere to load hydrogen atoms directly into the growing titanium crystal lattice.
- **Plasma Sources:** Experimental testing is currently underway using both Direct Current (DC) and Radio Frequency (RF) plasma heads to optimize thin film quality.
- **Thickness Constraint:** Film thickness is limited to approximately 50-60 nm to prevent excessive energy loss of the incoming $^{14}N$ ion beam inside the target.
- **The Analytical Problem:** Quantifying the tiny amount of trapped hydrogen (a few micrograms) embedded within the heavier titanium host matrix (approx. 120 micrograms) is an exceptionally difficult task for conventional surface analysis techniques.
- **Proposed Detection:** Direct measurement of the hydrogen content may only be feasible via in-beam nuclear reaction analysis using the accelerator itself.



