Determination of the Atomic Fraction in Intense Hydrogen Beams for Future Neutrino Mass Experiments

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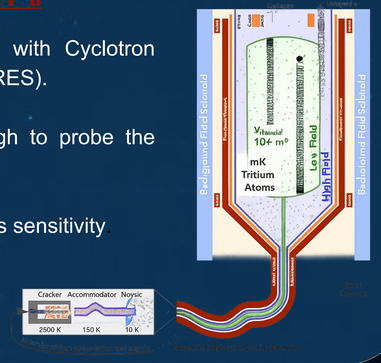
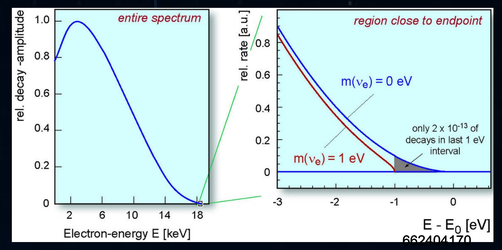
PROJECT 8

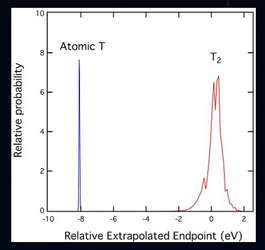
- Direct neutrino mass measurement with Cyclotron Radiation Emission Spectroscopy (CRES).
- Target sensitivity: 40 meV/c², enough to probe the inverted ordering.
- Atomic tritium is required to reach this sensitivity.



Introduction

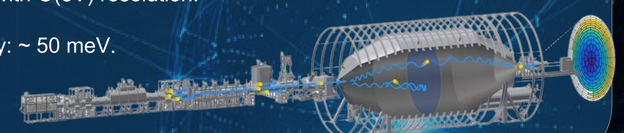
Neutrino mass influences the beta-decay spectrum in the endpoint region





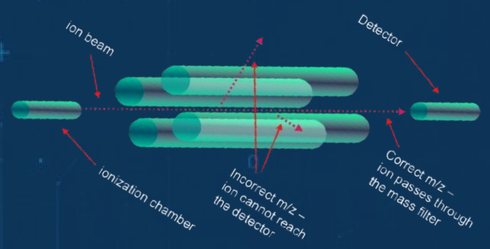
KATRIN ++

- Next-generation KATRIN extension.
- Atomic tritium source to remove molecular final-state broadening.
- Novel detector technologies for differential measurements with O(eV) resolution.
- Target sensitivity: ~ 50 meV.



Atomic Hydrogen Flux

The Hydrogen atomic flux is measured using a quadrupole mass spectrometer (QMS), which separates ions according to their mass-to-charge (m/z) ratio.



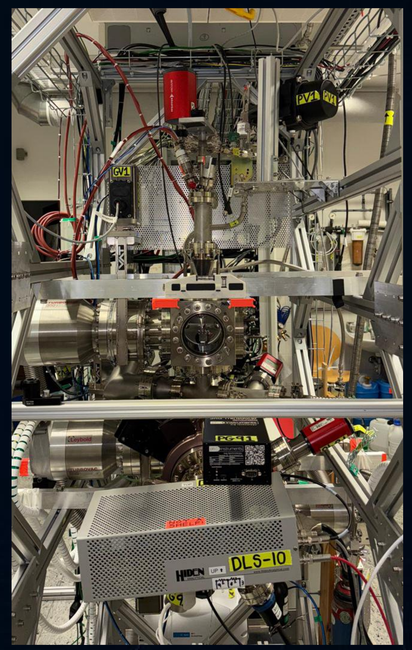
Ions with a specific m/z can reach the detector at a given voltage ratio

Analysis Approach:

The QMS signal m/z = 1 doesn't represents the atomic hydrogen, but it arises from multiple ionization processes, each with its own appearance potential.

process	apperance potential / eV
$H \longrightarrow H^+$	13.6
$H_2 \longrightarrow H^+$	18.1
$H_2 \longrightarrow {H_2}^+$	15.43

Mainz Atomic Hydrogen Beam Setup



Methodology

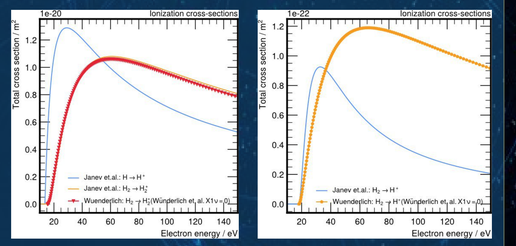
Count rate proportional to:

cross-sections x number density

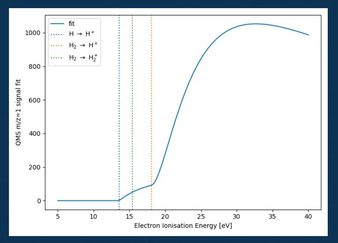
$$R_{m/z} = \sum_x \alpha_{m/z} \cdot \sigma_{x \to m/z}(E_{ion} + E_{shift}) \cdot n_x$$

σ: electron-impact ionization cross-sections [Rapp 1965; Shah 1987]. **E_{ion}:** set electron energy; **E_{shift}:** fitted energy-scale offset; **n_x:** number density of species z.

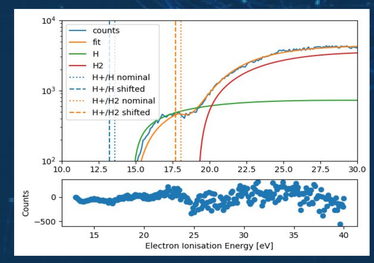
Theoretical cross-section calculations from the literature:



Cross-section with the different appearance potentials



Fitting the data to this model:



References

[1] KATRIN Collab., Science 388, 180 (2025) – m(ν) < 0.45 eV/c²
[2] Project 8 Collab., J. Phys. G 44, 054004 (2017); arXiv:1710.01826
[3] Janev et al., JÜL-4105 (2003).
4]] Wünderlich et al., JQSRT **110**, 62–71 (2009).
[5] K. G. Tschersich, J. Appl. Phys. 87, 2565 (2000); 104, 034908 (2008)
[6] NIST Chemistry WebBook – ionization / appearance energies

- UHV system for low background
- Thermal dissociator for atomic H production
- Beam diagnostics (wire detector & mass spectrometer)
- Differential pumping reduces H_2 background
- Skimmers collimate the beam
- Cryogenic cooling (accommodator & nozzle) for trapping

Current Status

Improvements to setup & atomic-flux analysis:

- Advanced modeling of ion extraction efficiency
- Multi-channel cross-section framework established

Data-taking resumed after the experimental setup was upgraded

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