Atomic Tritium: Phase IV of Project 8

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PRISMA Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter

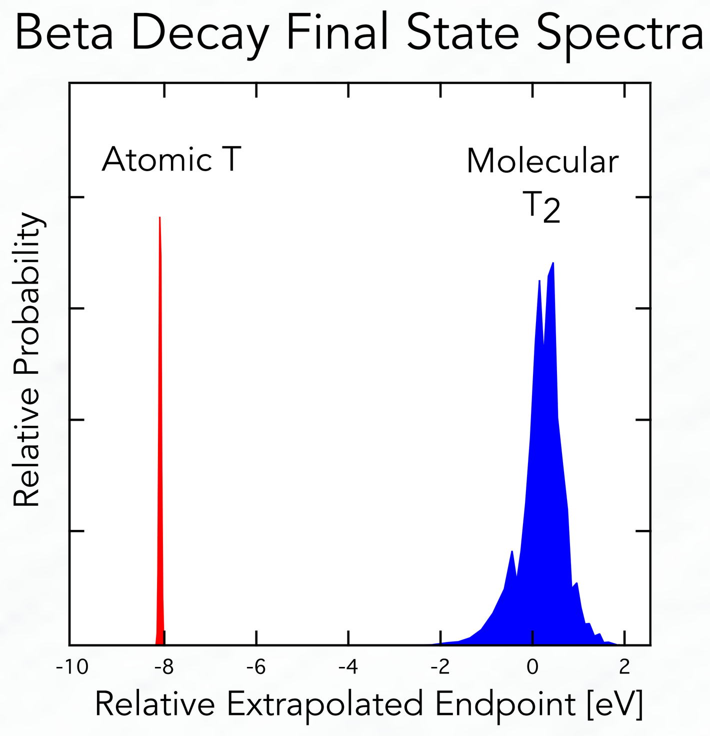
Project 8 and CRES

Project 8 plans to measure the neutrino mass using tritium beta decay, with a design sensitivity of 40 meV. Phase I of Project 8 pioneered a new technique, Cyclotron Radiation Emission Spectroscopy, that enables unprecedented neutrino mass reach. We have established the instrumental requirements for Phase IV of Project 8, the first direct neutrino mass experiment with atomic tritium, and identified candidate technical solutions for each requirement.

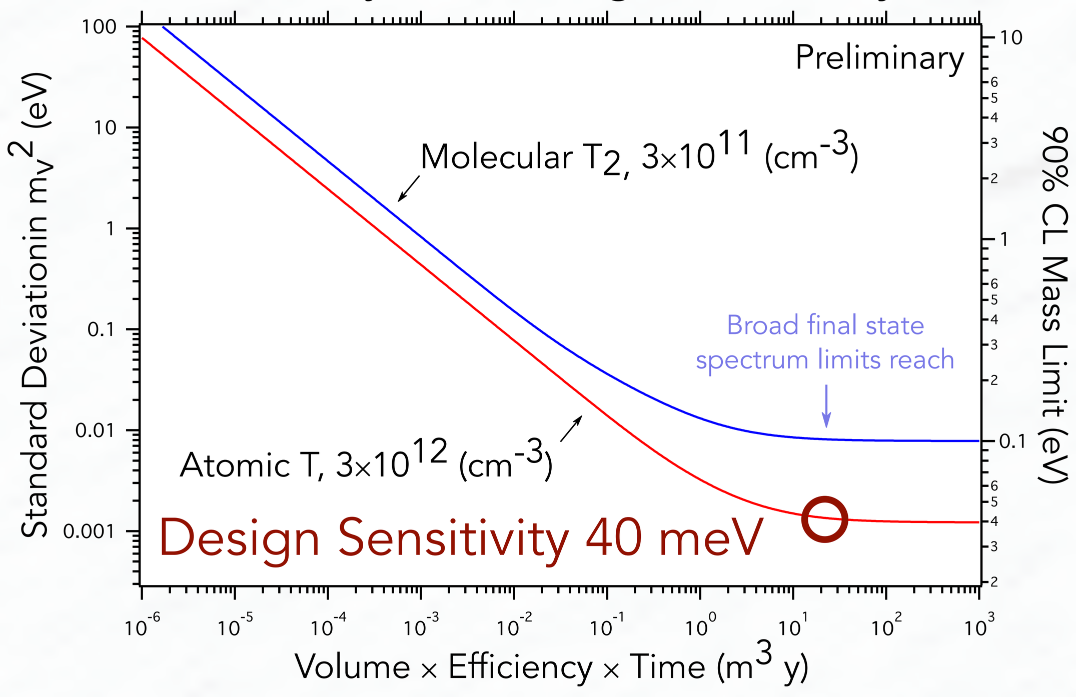
Why Atomic Tritium?

Molecular tritium has a wide final state distribution. This fundamental limit on energy resolution makes atomic tritium - with its sharp final state distribution - the best choice for neutrino mass reach below 100 meV.

Beta Decay Final State Spectra

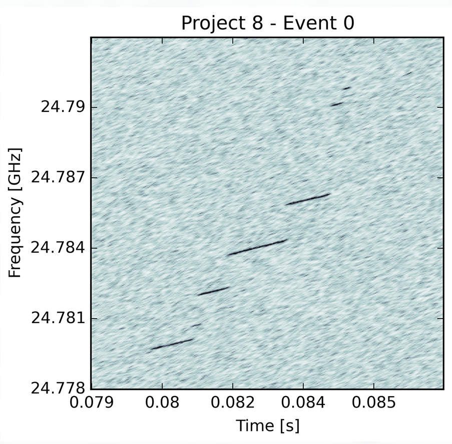


Project 8 Design Sensitivity



The CRES Technique

Measuring the energy of 18.6 keV electrons with eV resolution requires highly specialized methods. Project 8 has pioneered an entirely new technique, **Cyclotron Radiation Emission Spectroscopy**, that measures individual electron energies. CRES does not require extensive engineering to separate electrons from the source gas. With CRES of 83mKr at 30.4 keV, Phase I of Project 8 achieved 2.7 eV resolution.



Phase IV

Establishing a stable atomic tritium source requires an abundant flux of carefully prepared atomic tritium. We will dissociate molecular tritium in a thermal cracker, and cool it in four steps.

Atomic tritium recombines rapidly on most physical surfaces, but almost never in free space. Therefore, the ideal container for an atomic tritium population is a magnetic bottle. In the central fiducial region, Phase IV calls for:

- 10^{18} trapped atoms at 10^{12} cm^{-3} (10^9 Bq)
- $\leq 10^{-6}$ T_2/T ratio
- $\leq 10^{-7}$ magnetic field uniformity
- ≤ 1 cm position resolution in (r,ϕ) plane
- ≤ 1 eV electron energy resolution

Elements of Phase IV

1: Thermal Cracking

- Dissociation in a 2500 K tungsten tube
- High flux: $> 10^{17}$ atoms/s
- High atomic fraction: > 90% typical

2: Accommodator

- Cools to 160 K with collisions on aluminum
- Only 10^{-5} recombination probability per collision

3: Nozzle

- Cools to 4 K on a frozen deuterium film

4: Magnetic Velocity Selector

Only atoms with |v| < 20 m/s are trappable. Because of the subsequent magnetic step cooling, we select atoms up to 80 m/s. Two designs are under study:

4a: Magnetic thin lens

Exploits the dispersion of a thin lens, focusing various speeds to different points; beam stops reject fast, hot atoms

4b: Curved magnetic quadrupole

Cold, slow atoms follow a tube-shaped magnetic minimum; curves prevent direct transmission of hot atoms

Both designs benefit from the peaked angular distribution of the 4 K nozzle. In addition, they reject all residual molecules from the cracker.

5: Magnetic Step Cooling

Uses the CRES background field to slow the atoms entering from the selector

- ΔB = +1 T field step: Δv = - 60 m/s
- The 80 m/s atoms are now 20 m/s

6: Continuous Trap Loading

- The trap has an opening at one end
- Permits constant injection of cold atoms
- ~ 10^{14} cold atoms/sec required

7: Atom Trapping

- The atoms are held in a potential well
- The 2 T depth holds atoms up to 20 m/s

8: Electron Trapping

- The magnetic trap also holds the beta electrons for CRES measurement

9: Microwave Readout

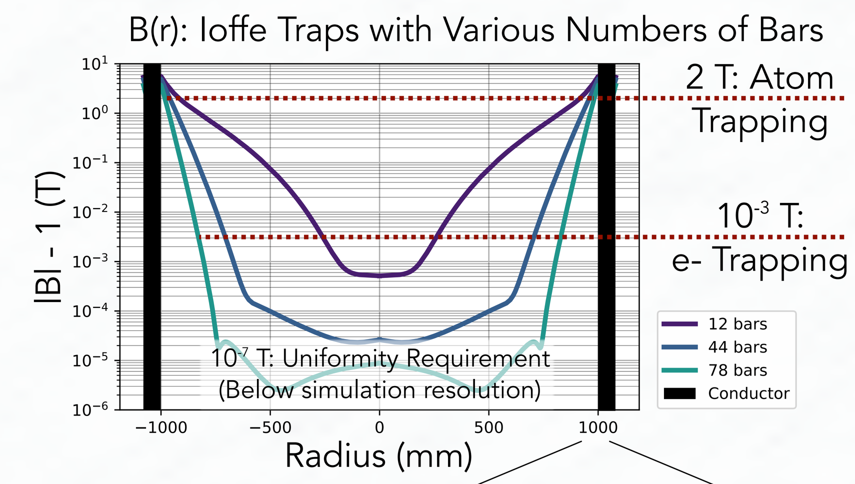
- Patch antennas outside the 3 T contour collect the cyclotron emission
- Digital beamforming gives position resolution of ~ 1 cm

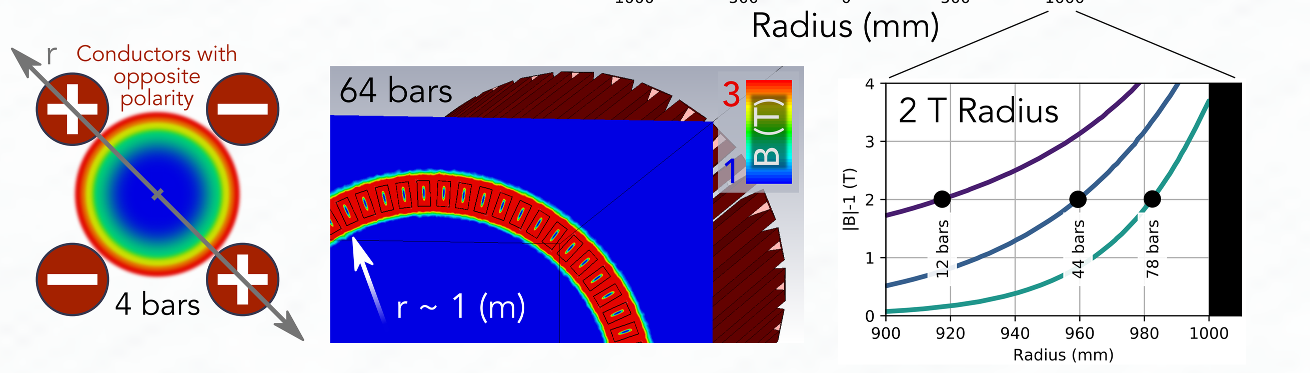
Atom Storage: The Ioffe Trap

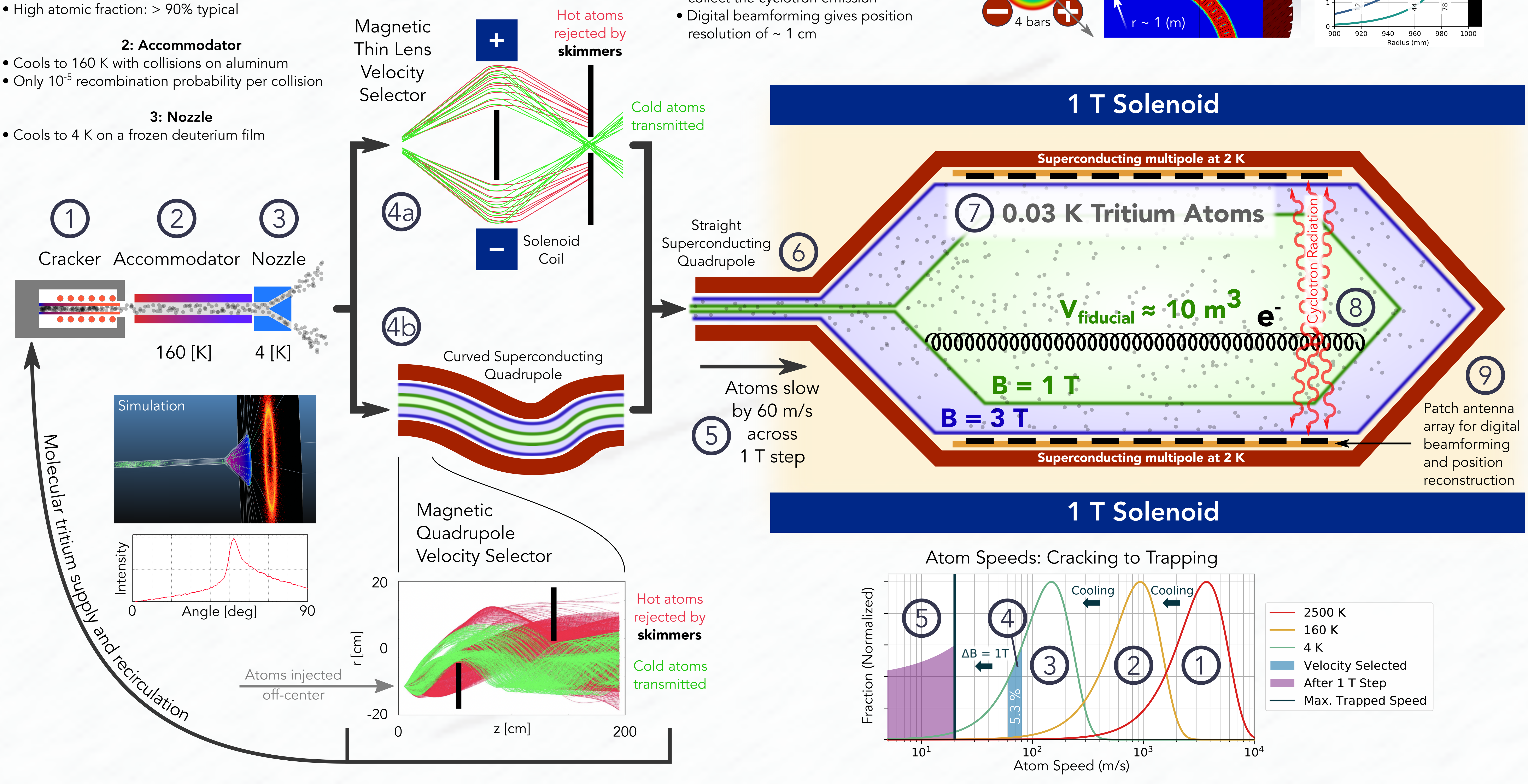
We use a superconducting, high-order magntic multipole to produce a magnetic minimum with a large uniform field region. Tritium atoms have a nonzero magnetic moment, and feel a potential in this magnetic field:

$$U = -\vec{\mu} \cdot \vec{B}$$

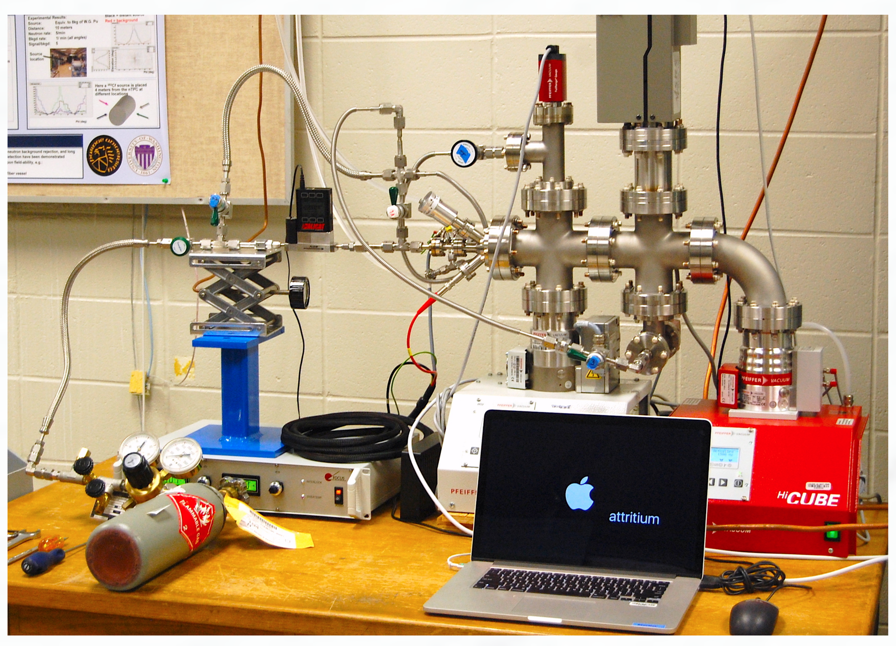
- Deepest practical trap: 2 T
  - Traps atoms ≤ 20 m/s
- Residual molecules escape
  - T_2 freezes to walls
  - Assures $T_2/T < 10^{-6}$
- Trap is loaded continuously



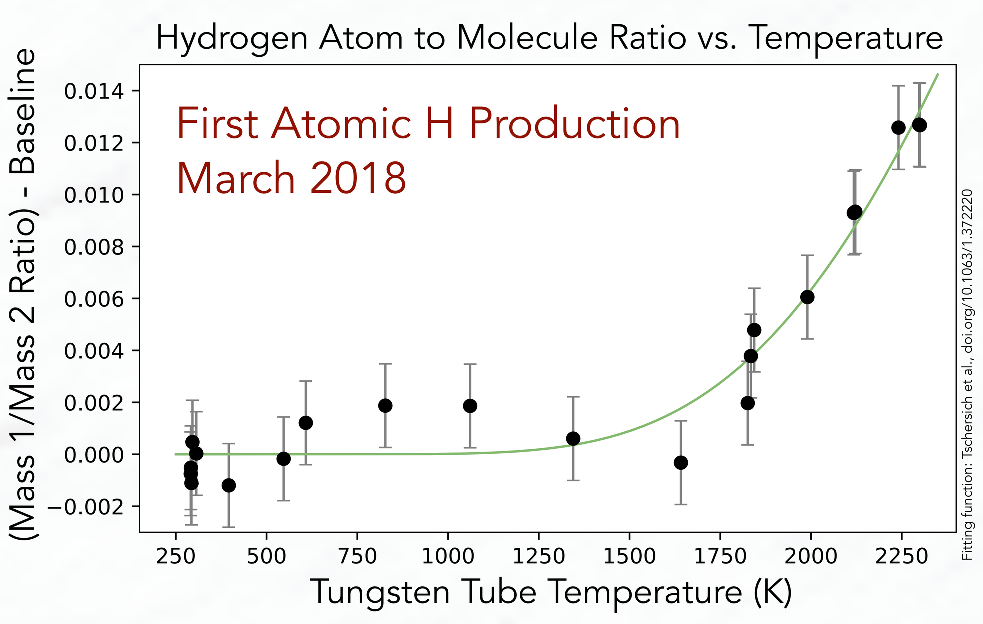


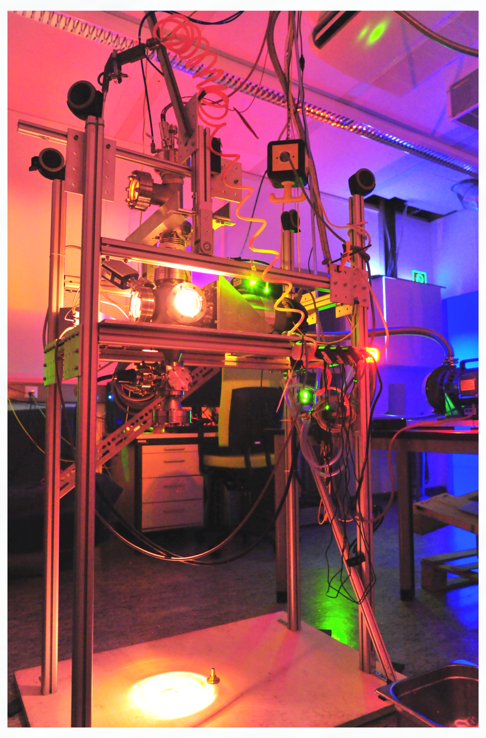


D_2 Cracker Test Stand



H_2 Cracker Test Stand





First Atomic Hydrogen

We have set up a thermal cracker in Mainz, and measured production of hydrogen atoms. The fit is from Tschersich et al., who developed this source. The detected atom/molecule ratio, including background outgassing, agrees with our gas dynamics simulations.

The Project 8 Collaboration

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