X-Ray Spectroscopy of Highly Charged Ions (HCIs) for Laboratory Astrophysics

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Motivation

- X-ray and EUV emission have been observed due to charge exchange (CX) from various sources like comets, heliosphere, earth's geocorona and exosphere and as well as extrasolar sources like supernova remnants, galaxy clusters, etc.
- JAXA/NASA launched X-Ray Imaging and Spectroscopy Mission (XRISM) on Sep, 2023 and aims to focus on these cosmic objects that emits X-rays.
- Our experimental results obtained in a controlled lab, can give exact cross sections, line intensities, and ratios for the given charge exchange and can help to understand different spectral features in the obtained X-ray data spectrum.

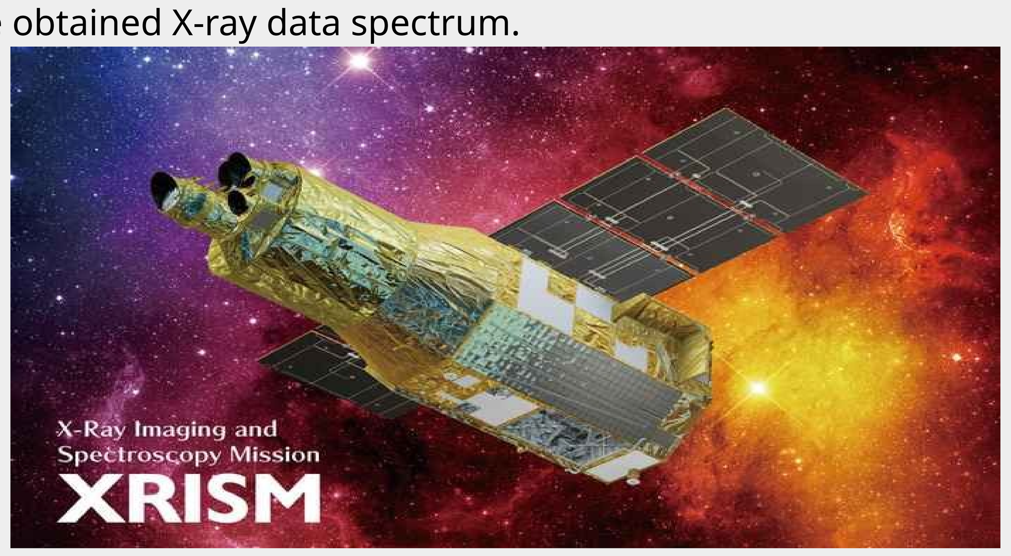

Fig 1: XRISM (X-Ray Imaging and Spectroscopy Mission) telescope

(https://api.uva.nl/content/news/2023/09/xrism.html)

Clemson University Electron Beam Ion Trap (CUEBIT)

- It produces highly charged ions (HCIs) from a neutral gas by interacting with highly densed and highly charged electron beam.
- The cathode generates electron currents up to several hundred mA, which are extracted by the anode at 10–15 kV.
- The electron beam is compressed inside the drift tube using 6T superconducting magnet which is cooled using liquid He.
- HCIs are axially confined inside the drift tube using two end-cap electrodes and radially confined due to electron beam.
- Extraction beam line guides the beam for further selection of the charge states and for focusing.
- Electromagnet positioned at 90^0 bent in the beamline is used to select ions with specific charge-to-mass ratio, allowing only those ions to continue down the beamline.

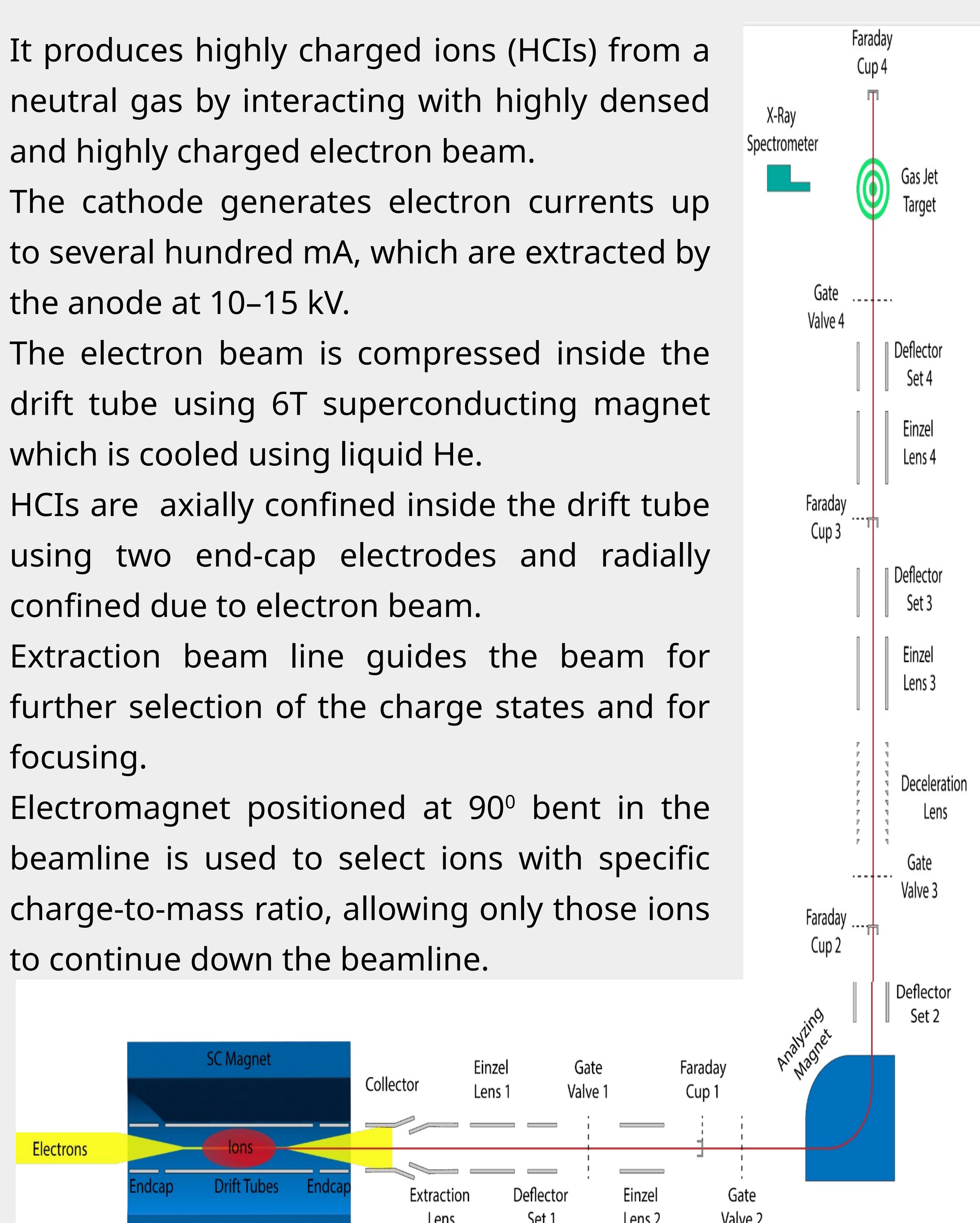

Fig 2: Diagram of CUEBIT

Charge Exchange

- It is a common collisional process at the interface between hot, ionized gas and cold media like supernovae remnants, galaxy cluster, etc.
- Electron(s) are captured from neutral atoms by ions into the excited state(s) which will under go cascade radiative transition to ground state.
- Most of the studies have been carried out for single electron capture (SEC) as it is a dominant process even for multi-electrons target. However, observations have showed that the multi-electron capture (MEC) becomes important for highly charged ions interacting with multi-electron targets at low collision energy.
- The charge exchange process can be expressed as:

$$P^{q+} + N \rightarrow P^{*(q-j)+} + N^{j+}$$
$$\rightarrow P^{(q-j)+} + N^{j+} + \gamma$$

Here, P is the projectile ion with q+ charge state, N is the neutral atom and gamma is the photon released due to the cascade radiative transition.

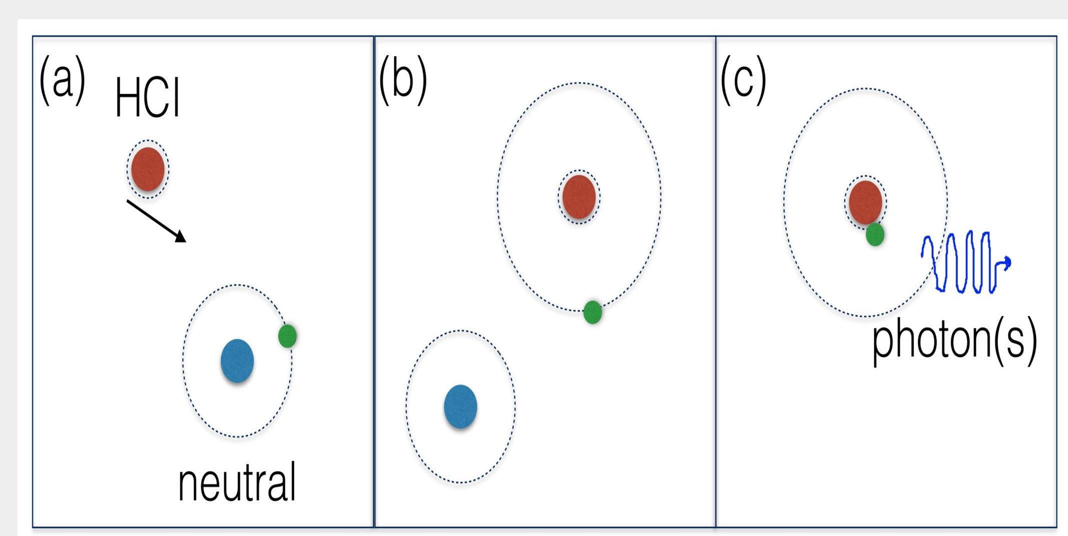

Fig 3: Schematic diagram of charge exchange process for highly charged ions (HCIs)

X-Ray Microcalorimeter

- Each detector consists of an HgTe absorber (625 x 625 x 8 μm) whose temperature increases by a tiny amount (often microkelvins) when an X-ray photon hits it.
- Attached to the absorber is a silicon thermistor (ion-implanted Si), whose resistance depends on temperature.
- Both the thermistor and absorber are kept at very low temperature (usually <0.1 K in a cryostat) such that even a minuscule heating is detected.
- The resulting voltage pulse is proportional to the energy of the absorbed photon.

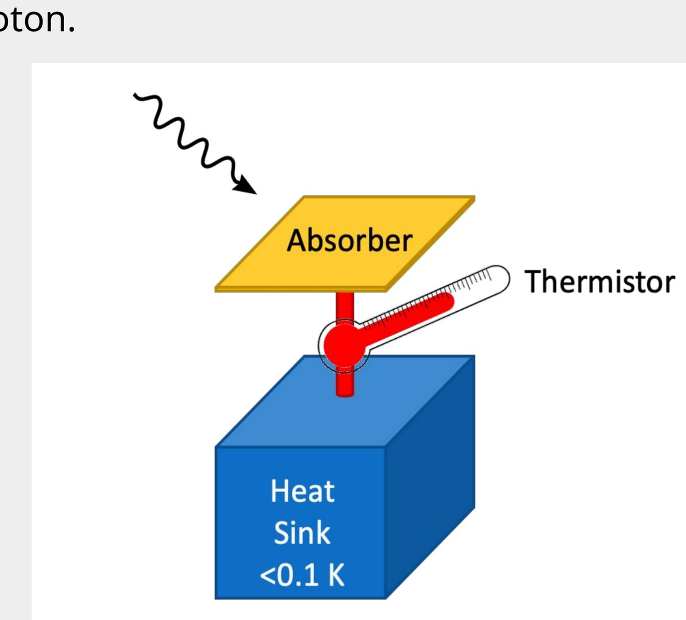

Fig 4: Diagram of X-ray Microcalorimeter

Current Work at Clemson

- We performed the charge exchange experiment between Ne^{10+} ions and neutral He and H2 at different collisional energy (0.25, 0.5, 1.0, 1.5, 5.96, 6.46 keV/u) and obtained the X-ray emission spectra and line ratios for He and H2
- Selected ions and neutral species (Ne, He, H2) are commonly observed in X-ray spectra from astrophysical sources like comets, solar wind interactions.
- These ions and neutrals are readily accessible in laboratory environment.
- Recently developed theoretical calculations and models (TDL, MCLZ, QMOCC) for these interactions can be directly compared, tested, and refined using our experimental results.

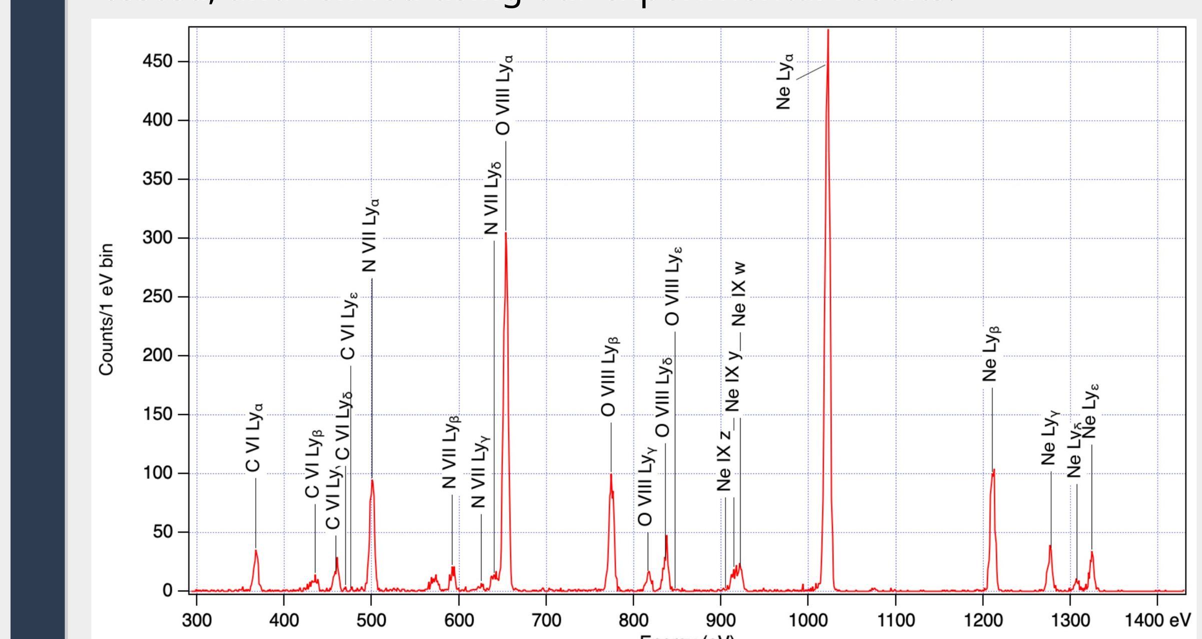

Fig 5: X-ray spectrum for $Ne^{10+} \rightarrow H_2$ at 0.25 keV/u collision energy

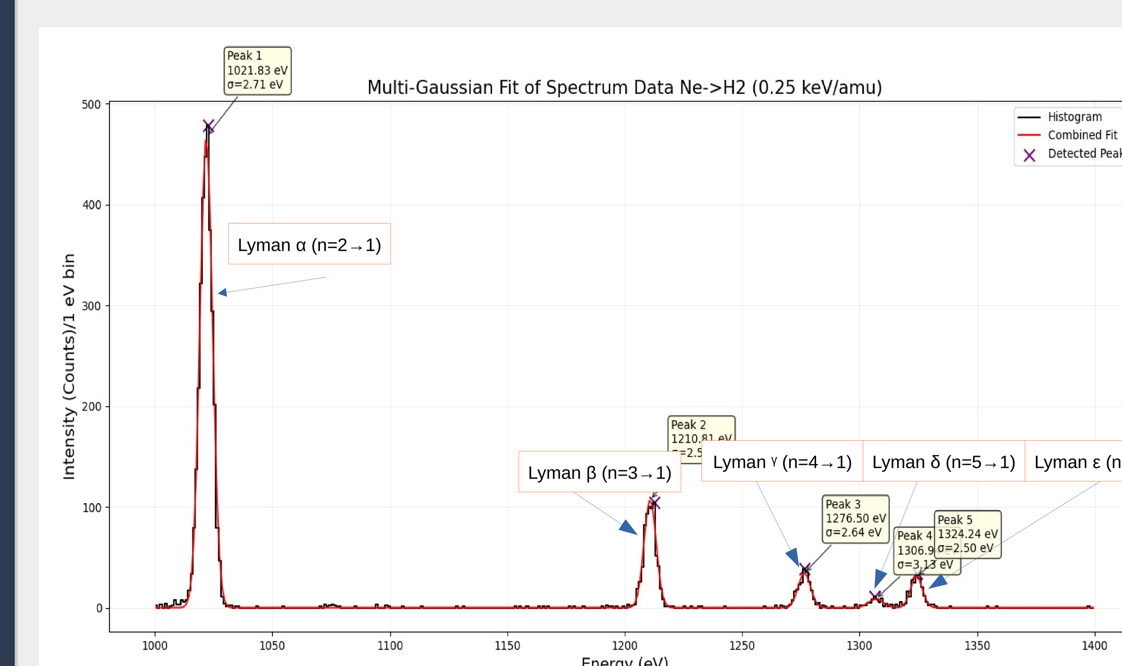

Fig 6: Multi-gaussian fit of X-ray spectrum for $Ne^{10+} \rightarrow H_2$ at 0.25 keV/u collision energy

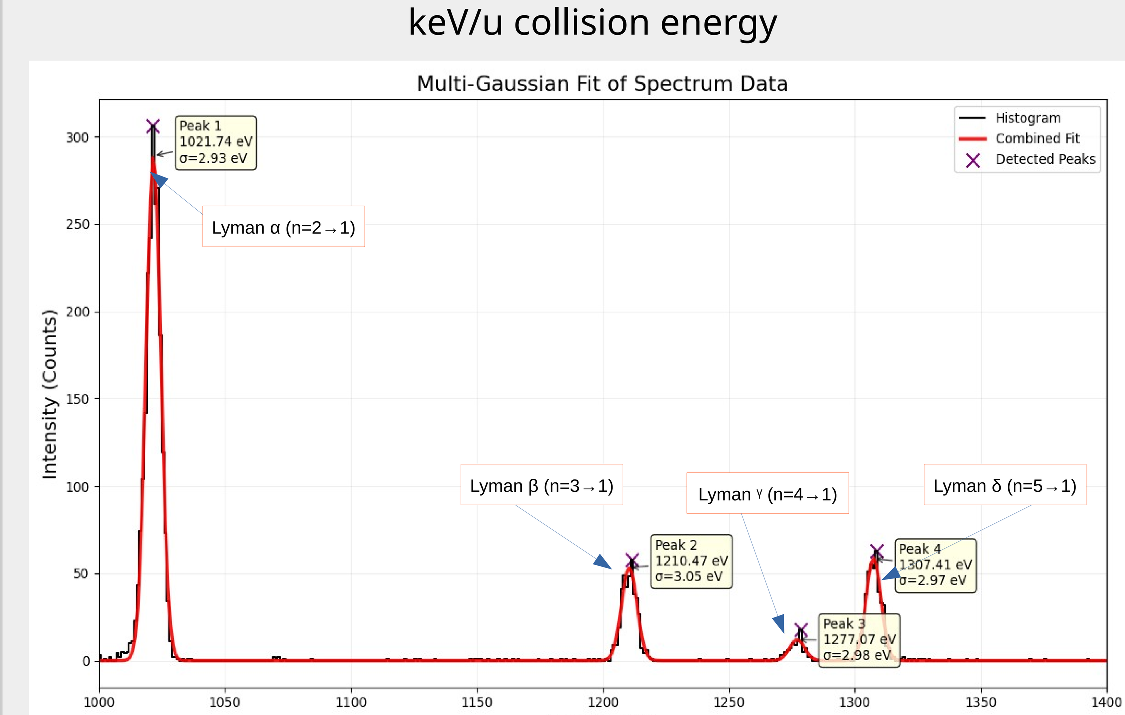

Fig 7: Multi-gaussian fit of X-ray spectrum for $Ne^{10+} \rightarrow He$ at 0.25 keV/u collision energy

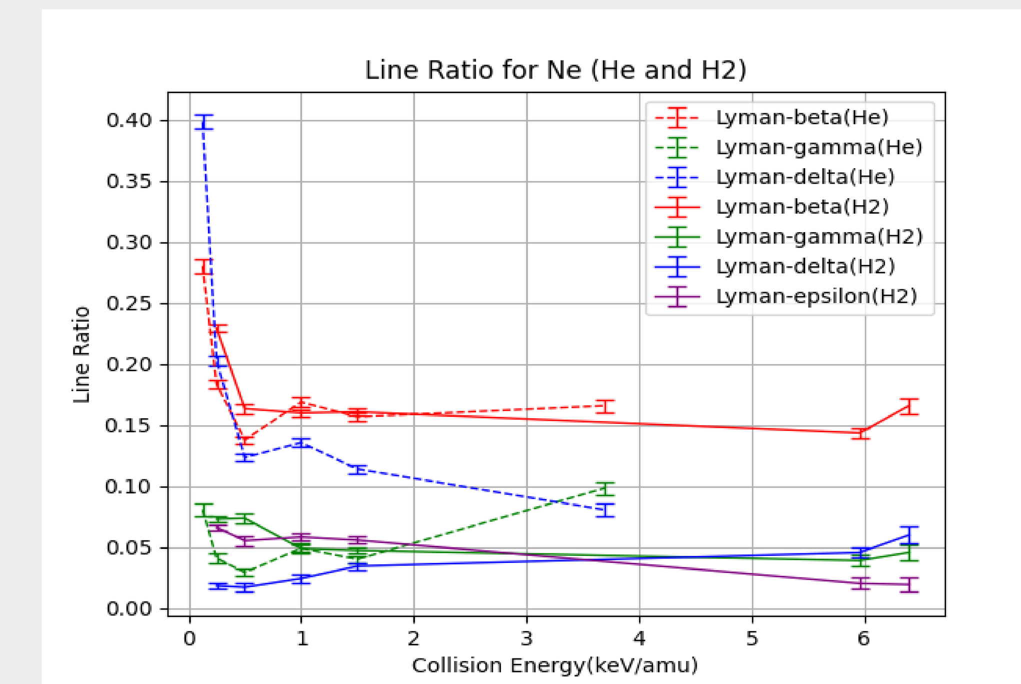

Fig 8: Comparative Line ratio of Bare Ne on He and H_2

- Different collision partners show different trends as a function of collision energy.
- Measuring the ratios of x-rays related to different transitions can tell you information about the collision energy and collision partners.
- We will continue to analyze current experimental data and compare it with theoretical data so to provide the framework for analyzing observed X-ray spectra.

Future Plan

COLTRIM

- Cold Target Recoil Ion Momentum Spectroscopy
- We are planning to transport and install the COLTRIM, data processing electronics, and supporting equipment from Auburn University to the CUEBIT facility.
- It can precisely measure the momentum of recoil ions/projectile, allowing the calculation of nl-resolved cross-section.
- It enables the identification of recoil ion and the final charge state of the projectile, allowing direct measurement of the relative contributions of SEC, MEC, and double capture autoionization in CX with H_2 and He.

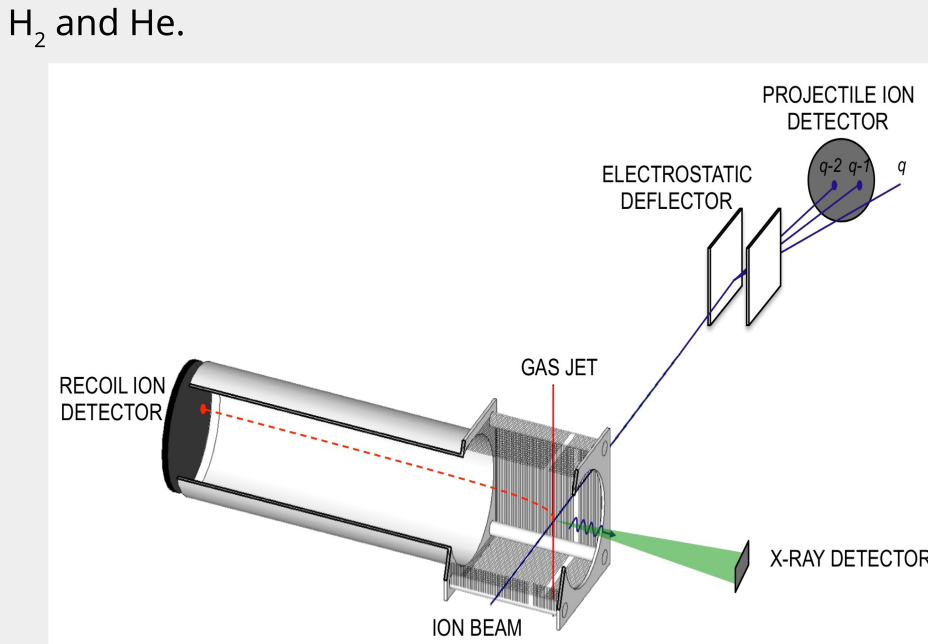

Fig 9: Schematic of the COLTRIM system

Acknowledgment

Auburn University, University of Georgia (UGA), NASA