Mass spectrometry of planetary exospheres at high relative velocity: Direct comparison of open- and closed source measurements

S. Meyer, M. Tulej and P. Wurz

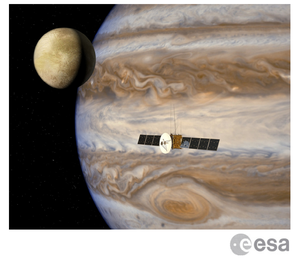
Physics Institute, Space Research and Planetary Sciences, University of Bern, Switzerland

Contact: stefan.meyer@space.unibe.ch

ABSTRACT

JUICE – **JU**piter **IC**y moons **E**xplorer a L-class mission of ESA, which will investigate and characterise Ganymede, Europa and Callisto as planetary objects and potential habitats [1], [2]. The current trajectory of JUICE foresees a flyby velocity of 4 km/s at Europa, other flybys are in the range of 1 up to 7 km/s and velocity in Ganymede orbits is around 2 km/s.

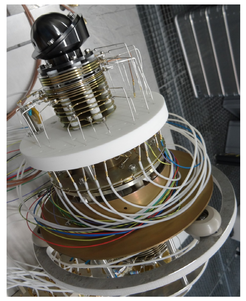
PEP – **P**article **E**nvironment **P**ackage carried by JUICE combines remote global imaging with in-situ measurements to study the atmospheres, plasma environments, and magnetospheric interactions and determine global surface compositions and chemistry, especially as related to habitability.
(PI: S. Barabash, Swedish Institute of Space Physics, Kiruna, Sweden,
Co-PI: P. Wurz, University of Bern, Switzerland)



NIM – **N**eutral gas and **I**on **M**ass spectrometer is part of PEP and will be used to measure the chemical composition of regular atmosphere produced by energetic particle and photon interaction with the surface of the icy Jovian moons (volatiles, contribution from non-ice material on the surface and isotopic composition of major species), as well as the ion composition of the ionospheres.

We developed a **prototype of the NIM**, part of PEP for the JUICE mission and performed measurements with the prototype instrument using a neutral gas beam of 1 up to 5 km/s velocity, containing different species in the neutral (open source) and thermal (closed source) mode. The results of these measurements with respect to fragmentation and density enhancements in the closed source mode are presented here. Furthermore, we give a direct comparison between open and closed source mode measurements.

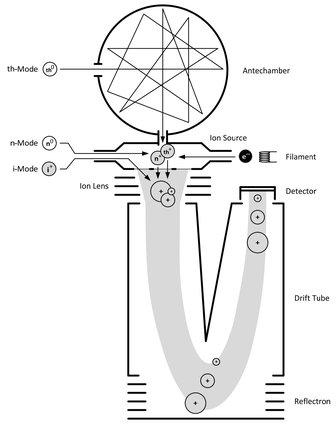
INSTRUMENT



NIM prototype

NIM (**N**eutral gas and **I**on **M**ass spectrometer) is a time-of-flight instrument with heritage from the RTOF sensor of the ROSINA instrument on the Rosetta mission [3] and the P-BACE instrument [4].

NIM can be operated in 3 different modes: **th-mode**, **n-mode** and **i-mode**, to measure the chemical composition of the inflowing neutral gas, as well as direct ions from the exospheres of the icy Jovian moons.



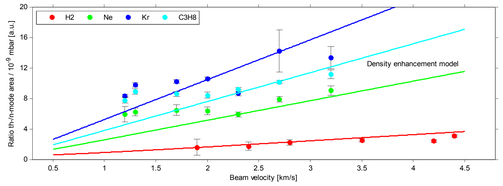
NIM scheme

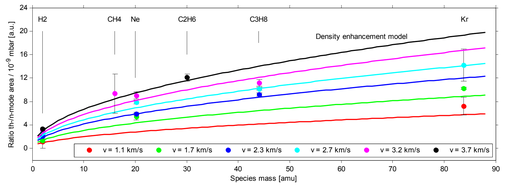
Thermal (th-)mode (closed source): neutrals (th^0) get thermally accommodated to wall temperature by several collisions inside an equilibrium sphere (antechamber) before entering the ion source and are then ionized by an electron beam, used for neutral gas measurements at any mission phase, mainly at Europa torus crossing and all other flybys.

Neutral (n-)mode (open source): neutrals (n^0) enter the ion source with spacecraft velocity and are then ionized by an electron beam, used for neutral gas measurements close to the moon (orbit or closest approach at flyby).

Ion (i-)mode (open source): ions (i^+) enter the ion-source with spacecraft velocity and are directly guided through ion-optics to the detector, used for thermal ion measurements close to the moon (orbit or closest approach at flyby).

BEAM VELOCITY RESULTS





Behaviour of the **antechamber (closed source)** together with the NIM prototype could be **successfully verified** for gas beam velocities of 1 up to 4.5 km/s, which covers the majority of JUICE mission phases, including Europa flyby and Ganymede orbit.

The verified mass range in n-mode and th-mode lasts from 2 (H_2) up to 84 amu (Kr), in which **NIM would support up to 700 amu for a 20 µs measurement**.

Density enhancement model is given by following formula from [5] and is primary velocity and mass dependant:

$$\frac{n_{cs}}{n_{os}} = \sqrt{\frac{T_n}{T_s}} \cdot \frac{F(S) \cdot k_2 \cdot \sin^2\left(\frac{\omega}{2}\right) \cdot \cos^2\left(\frac{\omega}{2}\right)}{1 - k_2 \cdot \cos^2\left(\frac{\omega}{2}\right)} \cdot \frac{d_i^2}{d_i^2 + d_s^2}$$

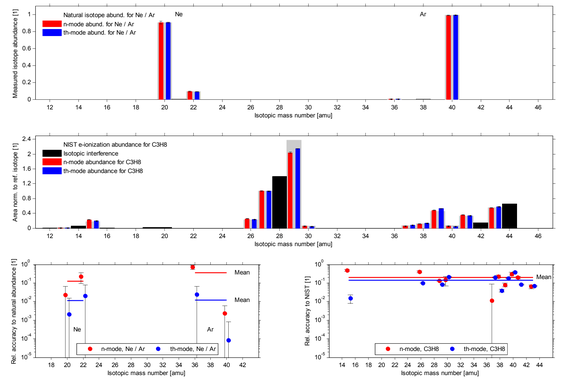
$$F(S) = e^{-S^2} + \pi^{\frac{1}{2}} \cdot S \cdot (1 + \mathrm{erf}(S))$$

$$S = v_{sc} \cdot \cos\chi \cdot \sqrt{\frac{m}{2k_B T_\alpha}}$$

where n_{cs} is the closed source number density, n_{os} is the open source number density, T_n the ambient gas temperature, T_s the ion source temperature, ω is the cone half-angle of the open source, v_{sc} the spacecraft velocity and χ its angle with respect to the entrance aperture and m the mass of the gas.

Measured area ratio th-mode/n-mode is **in good agreement with the density enhancement model** for noble gases like Ne and Kr, as well as molecules like CH_4, C_2H_6 and C_3H_8 and can be extrapolated for all JUICE mission phases.

ISOTOPE ANALYSIS RESULTS



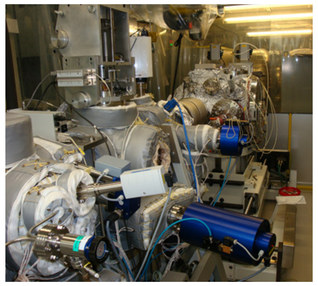
For the noble gases like Ne and Ar, its isotope abundance is compared with the natural table of isotopic abundances from [6]. The measured **relative isotopic accuracy to natural abundance** reaches from **100 ppm** for ^{40}Ar in th-mode up to almost 1 for ^{36}Ar in n-mode, depending on the signal-to-noise ratio (SNR) up to the detection limit. n-mode and th-mode mean accuracies are shifted due to the density enhancement, which also results in a SNR enhancement and therefore a better accuracy for th-mode.

For the molecules like C_3H_8 (Propane), its isotope abundance is compared with the NIST electron ionization abundance from [7]. The measured mean **relative isotopic accuracy to NIST electron ionization** abundance is between **10 to 20% for both n-mode and th-mode**, which is about the NIST measurement accuracy and suggests, together with the noble gas results, a much higher accuracy for the NIM prototype instrument.

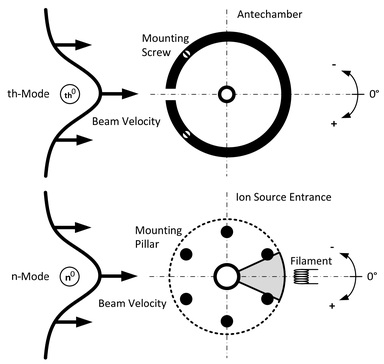
Moreover, the direct comparison of the n-mode (open source) and th-mode (closed source) gives **no evidence for any fractionation effects** inside the antechamber, since both modes measure almost the same composition, at least for the measured molecules H_2, CH_4, C_2H_6, C_3H_8, as well as Methanol vapour and Propanol vapour.

OPEN- AND CLOSED SOURCE MEASUREMENTS

We performed **measurements with the prototype NIM** using a neutral gas beam of realistic velocities in the n-mode (open source) and th-mode (closed source). To obtain a neutral gas beam at such velocities, the **CASYMIR** (**CA**libration **SY**stem for the **M**ass spectrometer **I**nstrument **R**osina) facility has been used. Different species and mixtures are used, such as noble gases Ne, Ar, Kr as well as molecules like H_2, CH_4, C_2H_6, C_3H_8 and more complex ones.



CASYMIR calibration facility

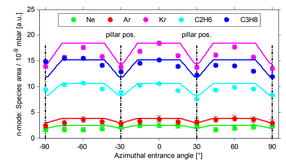


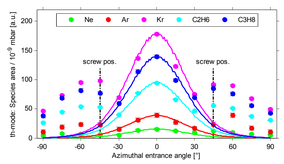
NIM instrument gas entrance scheme for both th-mode and n-mode

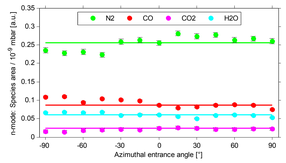
Measurement characteristics:

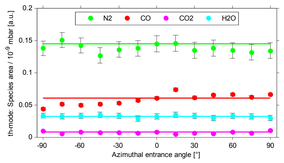
- **Beam**: ~ 10^{-9} mbar of gas, Gaussian profile with sigma ~ 10 mm at instrument entrance, velocity 1 up to 4.5 km/s.
- **th-mode**: antechamber (closed source) of 40 mm diameter with 4 mm entrance hole and DLC-coated inside (Gold-coated is also tested) with mounting screws at +/-45° from 0°-position, ionizing electron beam of 100 µA.
- **n-mode**: line-of-sight (open source) entrance 2 mm x 6 mm with mounting pillars of 4 mm every 30°, ionizing electron beam of 100 µA.
- **Rest gas**: ~ 10^{-10} mbar of rest gas in the UHV-chamber, mainly N_2, H_2O, CO, CO_2.
- **Azimuthal rotation campaign**: measurement of the gas mixtures at different azimuthal entrance angles (+/-90° from 0°-position) for both n-mode and th-mode, at the same velocity for each gas mixture (2 up to 3 km/s)
- **Velocity campaign**: measurement of the gas mixtures at different velocities (1 up to 4.5 km/s) for both n-mode and th-mode, at 0°-position.

AZIMUTHAL ROTATION RESULTS









n-mode is expected to be **independent with respect to the azimuthal entrance angle**. This could be verified with the open source measurements ranging from -90° to +90°, which only show a damping of the signal with the mounting pillars in line of sight.

th-mode is in space expected to be **modulated by a cosine of the angle between entrance aperture of the antechamber and the spacecraft velocity**. For the th-mode measurements, an additional modulation with the Gaussian gas beam profile is observed around +/-30°. Unexpected side-lobes occur with maxima at +/-45°, most probably due to scattering of the gas beam with the mounting screws of the antechamber.

The **rest gas** in the vacuum chamber is **rotationally independent for both n-mode and th-mode**, which is shown by the measurement of the rest gas species N_2, CO, CO_2 and H_2O in n-mode and th-mode.

CONCLUSION

- **NIM prototype** is **successfully tested** under realistic JUICE mission conditions.
- **Antechamber (closed source) behaves as expected with predictable density enhancement** over the specified mass range and within the JUICE mission phase velocities.
- n-mode (open source) and th-mode (closed source) measure almost the same composition for noble gases, as well as for molecules, indicating **no additional fragmentation of the species inside the antechamber**.

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