Scientific activities in ARIBE
the low-energy ion beam facility at GANIL

Patrick Rousseau

Aribe @ GANIL

Outline

History

Hall D was initially dedicated to ion source developments.

2000 LIMBE, two beamlines for users

2005 ARIBE, three additional beamlines

2010 GTS ion source is installed

2018 GTS upgraded

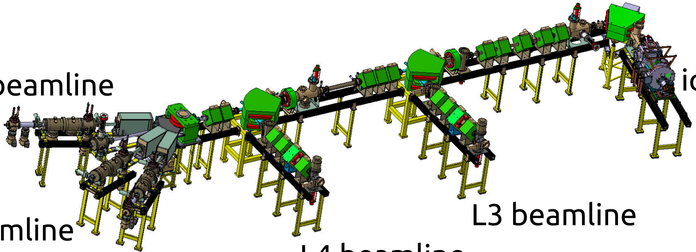
2021 ARIBE updated

ARIBE: accelerator

ARIBE accelerator is composed by :

- 1 electron cyclotron resonance (ECR) ion source ;
- 5 beamlines where end-stations can be mounted.

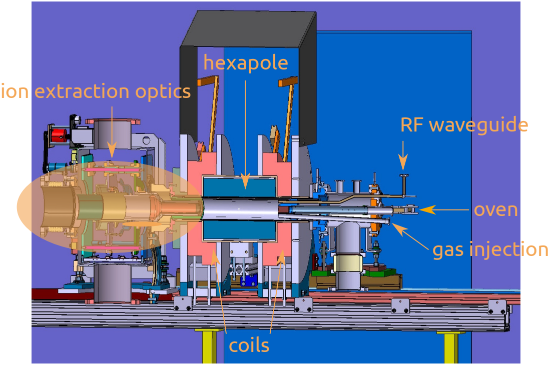
The accelerator was **updated in 2021** (vacuum and ion optics ctrl/cmd).



ARIBE: GTS ions source

The **GTS ECR ion source** allows to produce a large variety of ions with **different charge state**: He^{2+}, O^{6+}, Ar^{11+}, Xe^{25+}...

Typical **acceleration voltage**: 10-15 kV

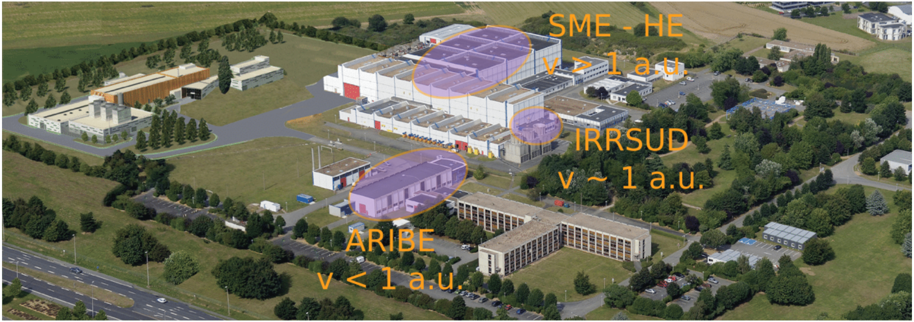


Ion beam map

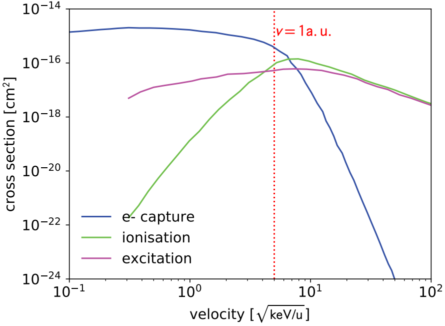
ARIBE is the low-energy ion beam facility of **GANIL**.

It delivers **slow ions**, i.e. with velocity below one atomic unit of velocity, thus slower than electrons in matter.

It complements the “offer” to interdisciplinary physics users. Ciril



Electronic processes: cross sections



Collisions $H^+ - H$

[D. Vernhet et al., *Nucl. Instrum. Meth. B* **107** (1996) 71]

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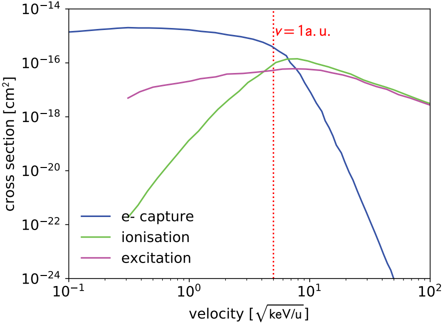
$\sigma_{\text{e-capt}} \sim 10^{-15} - 10^{-14}\ \text{cm}^2$



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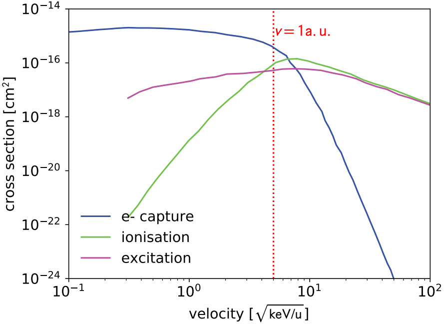

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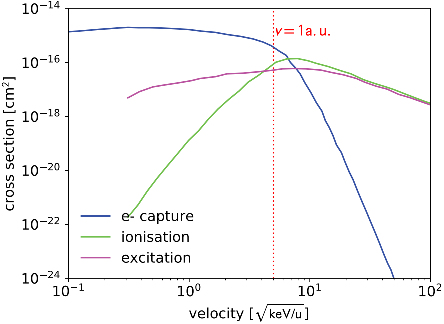

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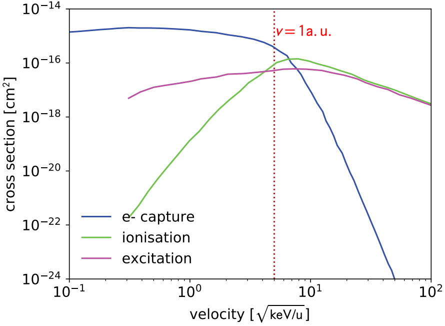
In the intermediate regime, all processes occur with similar cross sections.

$\rightarrow$ maximum energy deposit

$\rightarrow$ **Bragg peak**



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Electron capture

ARIBE delivers low-energy (few keV) ions thus **slow** ($v < 1$ a.u.).

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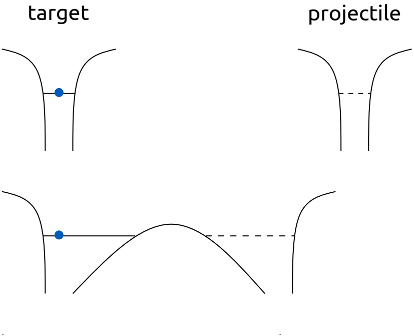

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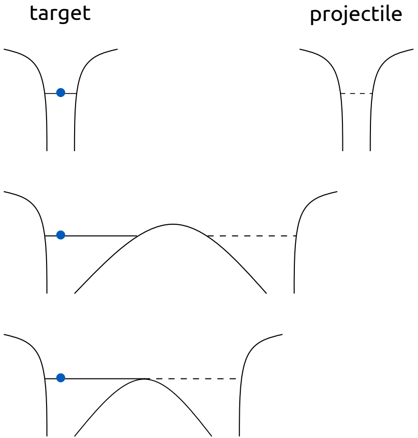

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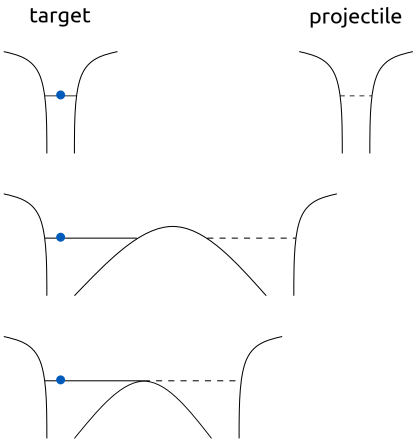
Classical-over-barrier (COB) model

Stronger barrier lowering with higher projectile charge state

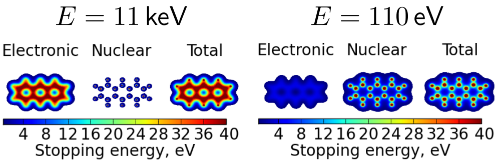
With multiply charged ions, (multiple) capture at **large distance** → **“cold” molecular ions**

Large yield of multiply charged molecular cations



Due to its mass, an atomic projectile can interact with both electrons and nuclei:

$\mathrm{He} + \mathrm{C}_{14}\mathrm{H}_{10}$



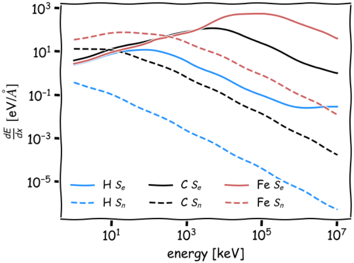
[Tao Chen, PhD thesis, Stockholm University]

Due to its mass, an atomic projectile can interact with both electrons and nuclei:

- the **nuclear energy loss** is due to elastic binary nucleus-nucleus collisions

Energy loss in anthracene $C_{14}H_{10}$

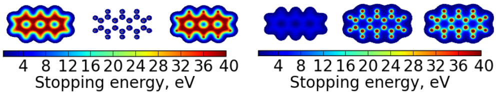
[calculated by SRIM http://www.srim.org/]



$He + C_{14}H_{10}$

$E = 11\,\mathrm{keV}$ $E = 110\,\mathrm{eV}$

Electronic Nuclear Total Electronic Nuclear Total



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Energy loss: stopping power

Due to its mass, an atomic projectile can interact with both electrons and nuclei:

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- the **electronic energy loss** is due to the friction of the projectile on the electronic cloud

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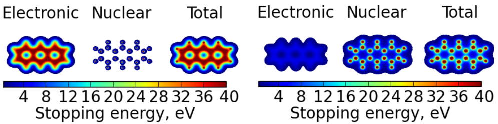

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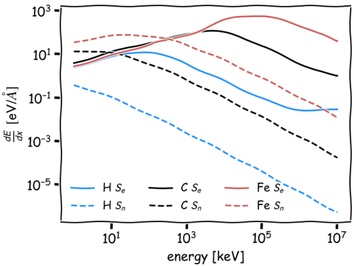

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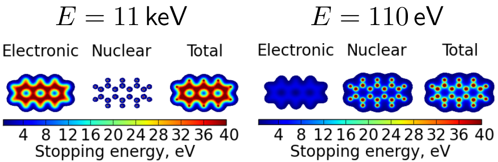

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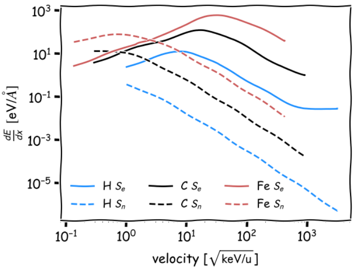
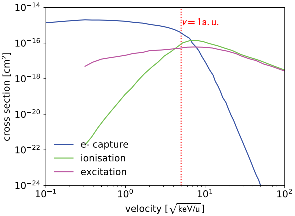
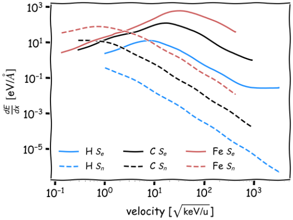


Take home message #1

Ion interaction leads to:

1. **electron removal**
   - by electron capture at low velocity
   - by ionisation at higher velocity
2. **energy deposit**
   - by nuclear energy loss at low velocity
   - by electronic energy loss at higher energy



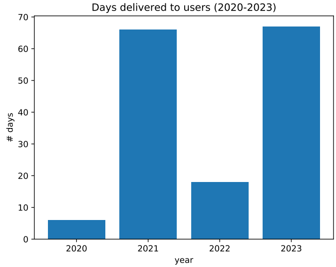


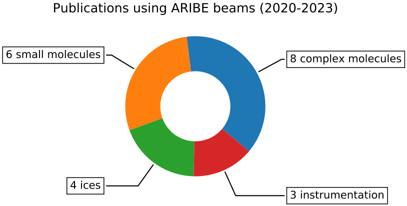
With **ARIBE beams**, electron capture dominates and nuclear energy loss is not negligible.

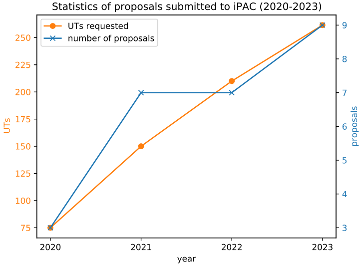
ARIBE offers a **flexibility** in the choice of **projectile nature and charge state**.

Outline

2020-2023 statistics







One PhD per year at CIMAP
plus PhD students of users.

Users come from:

Caen	CIMAP, GANIL
France	Paris, Marseille, Grenoble...
Europe	Italy, Sweden, Czech Republic...
World	India, Brazil, USA...

Outline

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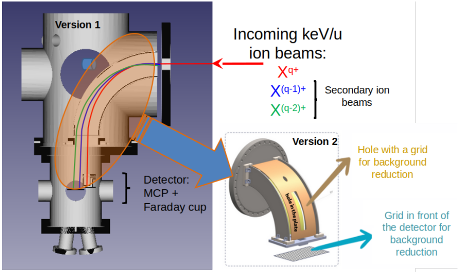
Instrumentation developped for FISIC project

FISIC: Slow ion - fast ion collisions
→ measurements of **cross sections in the intermediate region**

Test of instruments at ARIBE in 2021 and 2023.

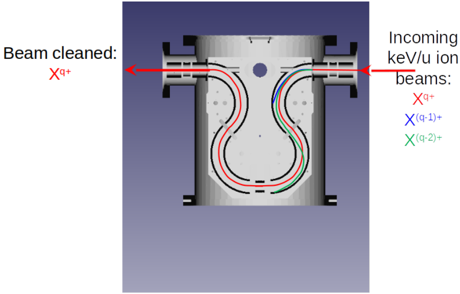
Ion spectrometer

[M. Jolly et al., *Atoms* **10** (2022) 146]



Charge state purifier

[D. Schury et al., *Rev. Sci. Instrum.* **90** (2019) 083306]



Instrumentation developped for FISIC project (2)

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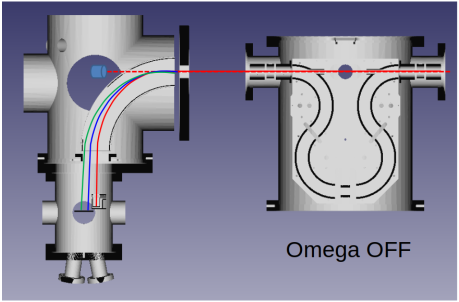

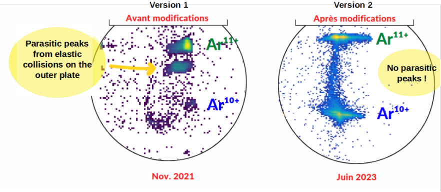

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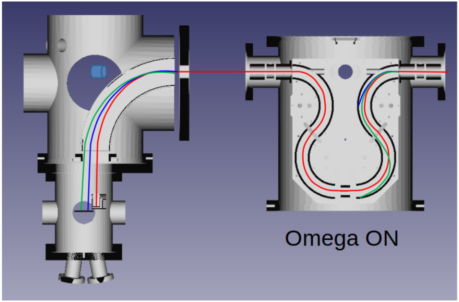
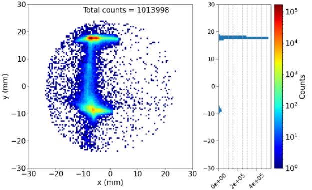
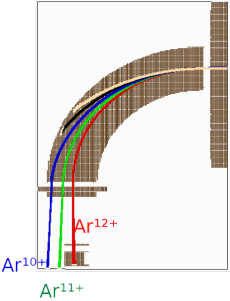






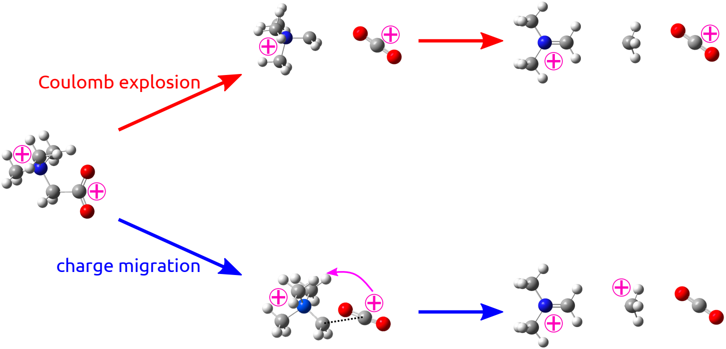
From the recorded counts on the MCP (Ar^{11+}, Ar^{10+}), the intensity of the main beam (Ar^{12+}) on the Faraday cup, and a set of coupled differential equations, it is possible to extract **capture cross sections** from N_2.

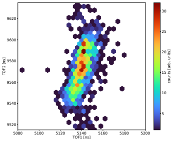
process	calculated CS	extracted CS
$Ar^{12+} \rightarrow Ar^{11+}$	$1.33 \cdot 10^{-14}\, cm^2$	$(1.43 \pm 0.74) \cdot 10^{-14}\, cm^2$
$Ar^{12+} \rightarrow Ar^{10+}$	$2.88 \cdot 10^{-15}\, cm^2$	$(1.78 \pm 0.95) \cdot 10^{-15}\, cm^2$

Outline

Charge migration vs. Coulomb explosion

Beside the expected **"Coulomb explosion"** we observe **charge migration**.

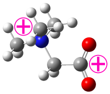




Scenario of charge migration in betaine dication

1. **two charges localised at both ends** due to electron captures

[P. Rousseau et al., *Science Adv.* **7** (2021) eabg9080]



①

Scenario of charge migration in betaine dication

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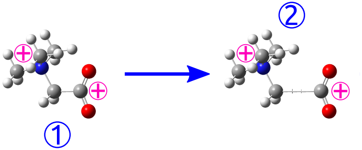
[P. Rousseau et al., *Science Adv.* **7** (2021) eabg9080]



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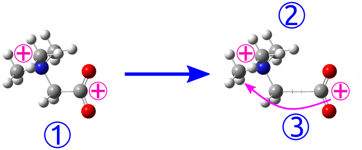

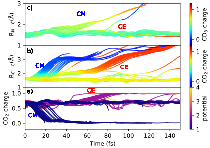

Scenario of charge migration in betaine dication

1. **two charges localised at both ends** due to electron captures
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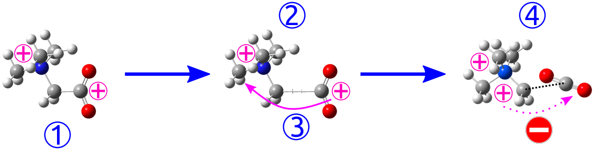
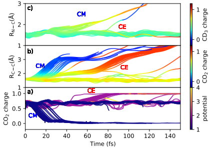
4. formation of a **transient species cutting the way back** for charge

[P. Rousseau et al., *Science Adv.* **7** (2021) eabg9080]





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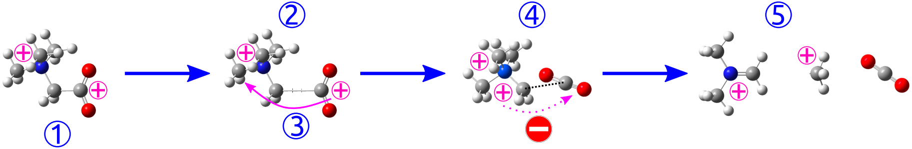
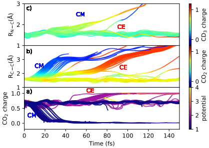
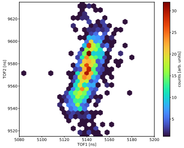
4. formation of a **transient species cutting the way back** for charge
5. emission of **two charged fragments** in the **same direction**

[P. Rousseau et al., *Science Adv.* **7** (2021) eabg9080]





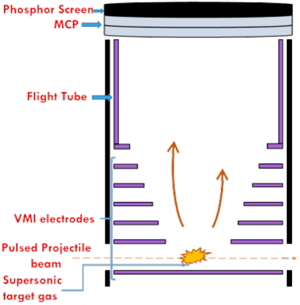


Ion-induced molecular fragmentation: case of N_2

Measuring **fragment ion KE and emission angle** with a **Velocity Map Imaging spectrometer**.
→ information on collision processes and fragmentation dynamics

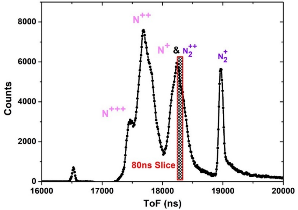
IMAGERI VMI spectrometer

[N. Sens et al., *Rev. Sci. Instrum.* **93** (2022) 085103]



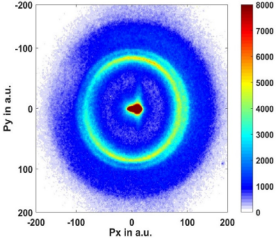
Time-of-Flight mode

→ identify ions



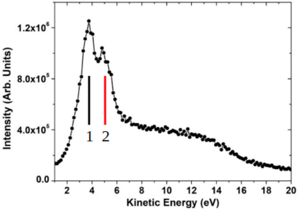
Imaging mode

→ velocity of selected ions



Ion-induced molecular fragmentation: case of N_2 (2)

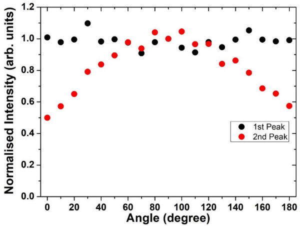
KE distributions of N^+ ions



Coulomb explosion

$N_2^{2+*} \rightarrow N^+ + N^+$

Emission angle vs. KE



Second peak shows **anisotropy** distribution peaking at 90°

To understand the **orientation dependence** of N_2^{2+*} dissociation

$\rightarrow$ collision processes (electron capture, transfer ionisation etc.) depend on **projectile charge state and velocity**

$\rightarrow$ iPAC2023 : 12keV-$He^+ + N_2$ (ARIBE); 35MeV-$Ar^{10+} + N_2$ (IRRSUD)

Take home message #2

Collisions with slow multiply charged ions allows to produce **multiply charged molecular ions**.

The problem of the distributions of initial states can be overcome using **coincidence measurements**.

"Coulomb explosion" of the molecular systems can give information on the **dynamics timing** even without pump-probe scheme.

→ **Nuclear dynamics** observed (e.g. atom migration)

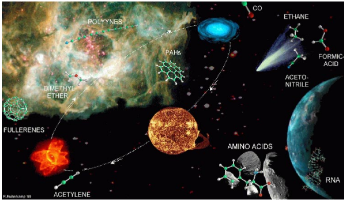
→ **Electronic dynamics** observed (e.g. ICD, charge migration)

Outline

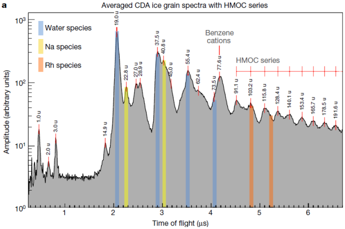
Molecules in space

We are living in a **molecular universe**.

Both **neutral and ionic species** have been identified (+200 species).
Complex organic molecules observed in meteorites, on Saturn moons.



Enceladus dust particle mass spectra
[F. Postberg et al., *Nature* **558** (2018) 564]



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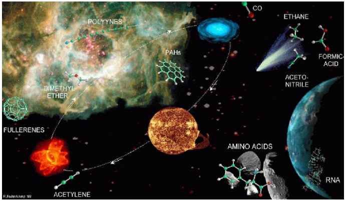
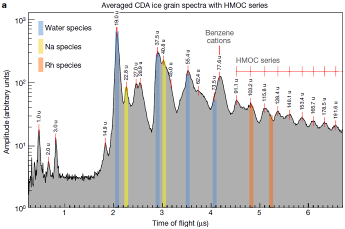
Molecules are **exposed to ionising particles** (photons, electrons, ions).
What is the role of **energetic processing by radiation** on growth processes?



Enceladus dust particle mass spectra
[F. Postberg et al., *Nature* **558** (2018) 564]

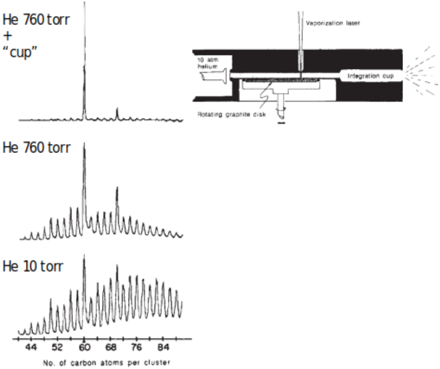


Bottom-up, Top-down, What else?

Two approaches are usually considered to produce complex molecules.

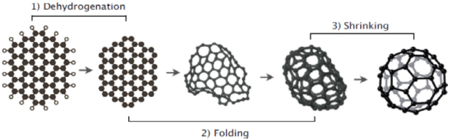
Starting from small units to grow
→ **"bottom-up"**

Laser vaporisation of graphite
[H. W. Kroto et al., *Nature* **318** (1985) 162]



Processing large particles of matter
→ **"top-down"**

Processing of large PAH
[O. Berné et al., *A&A* **577** (2015) A133]



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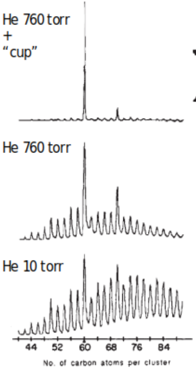

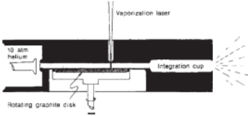

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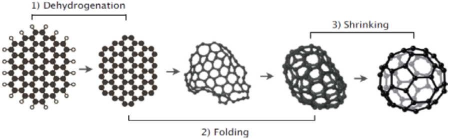
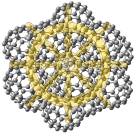
[O. Berné et al., *A&A* **577** (2015) A133]



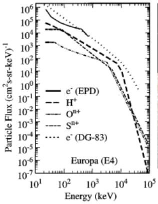
“middle way”
→ reactivity inside molecular clusters

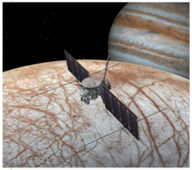


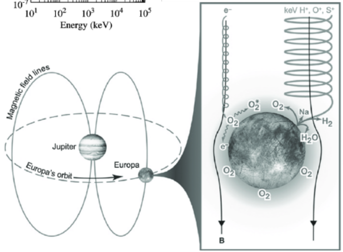
Implantation of sulfur ions in ices

Europa is impacted by low energy ions from Jupiter magnetosphere.

Production of **organosulfur compounds** by implantation of **S^{q+} ions**?

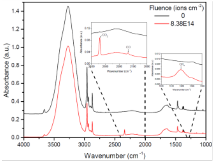


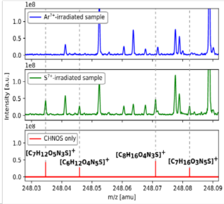


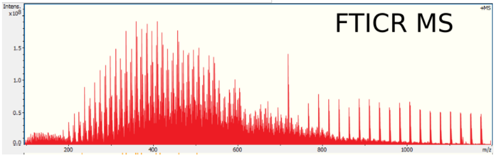


Irradiation of H_2O : C_3H_8 ice by 105 keV S^{7+} ions

FTIR spectroscopy



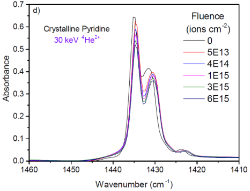


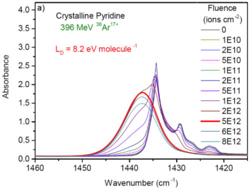


Irradiation of complex organic molecules

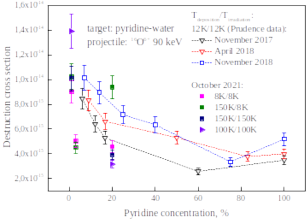
Amorphisation and destruction of COM ices on planet moons

Amorphisation of pyridine ices





Destruction of pyridine ices



Preliminary results show:

- amorphisation by SHI (Ar@SME)
- no amorphisation by low-energy He^{2+}

→ looking for the **effect of heavier** (O, S) low-energy ions

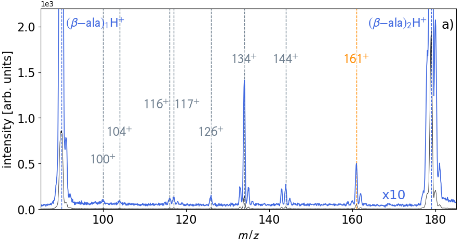
Higher destruction yield in **mixed ices** water:pyridine
→ need to consider mixed ices in models

Formation of peptide bonds

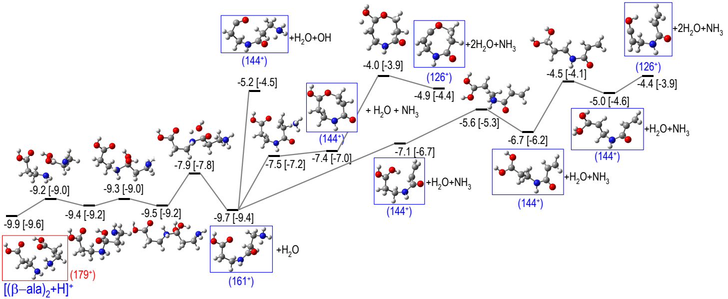
Successive losses of 18 mass units
from the β-alanine clusters
$\rightarrow$ **peptide bond formation?**

Similar patterns observed
$\rightarrow$ same mechanisms?

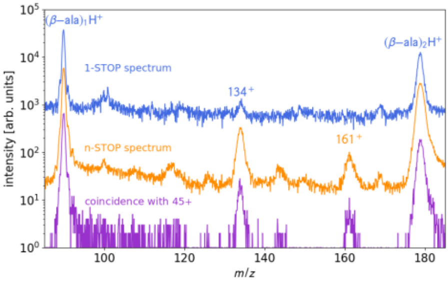
30 keV He^{2+} collisions with $[\beta - \text{ala}]_k$
[P. Rousseau et al., *Nature Commun.* **11** (2020) 3818]

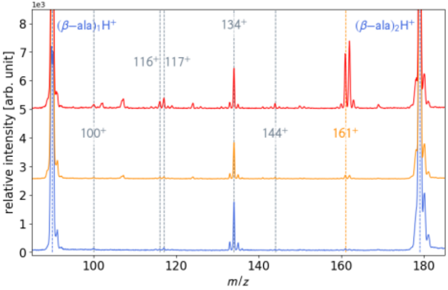


Potential energy surface exploration



Formation of peptide bonds (2)





More peptide bond formation:

- for **multiply charged clusters** → role of charge, energy transfer
- for **larger initial clusters** → excess energy is dissipated

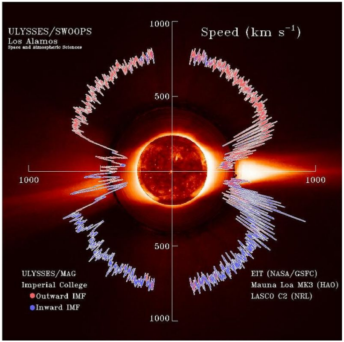
Peptide bond formation also observed in glycine clusters (July 2023)

Looking for **chiral effect** in peptide bond formation (March 2024)

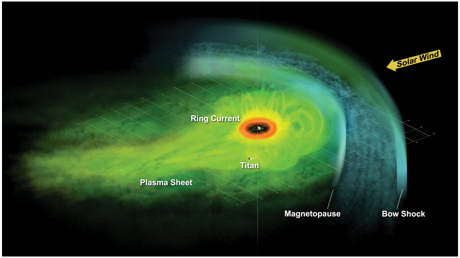
Take home message #3

Ion collision induced **reactivity** observed in both condensed (ices) and gas phase (clusters)
→ **formation of complex molecules**
→ **role of low energy ions** in space molecular inventory wealth

Solar wind



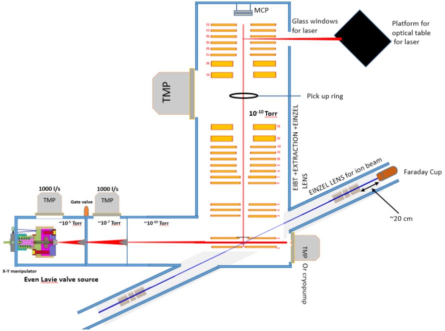
Giant planet magnetosphere



Outline

New instruments for reactivity studies

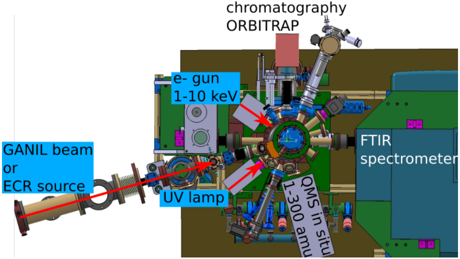
FRAPA



ANR and FEDER

Know-how acquired could be used to **develop molecular ion storage device** for users.

MIRRPLA



PEPR Origins (France 2030)

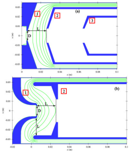
Unique device to study the **irradiation of astrophysical ices analogues**

ARIBE: a solar wind simulator

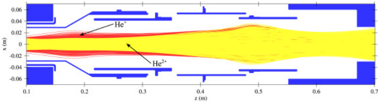
low energy extraction

(collaboration IAP Nizhny Novgorod)
[S. S. Vybin et al., *Nucl. Instrum. Meth. A* **1061** (2024) 169109]

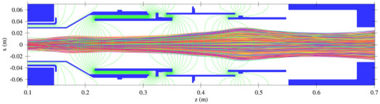
new electrode design



He^{q+} extraction voltage 2 kV



Xe^{q+} extraction voltage 1 kV



"metallic" ions

There is a need to produce new ion beams such as:

- Mg
- Si
- Fe

→ to install the MIVOC method on the GTS source

Alternative solution to produce sulfur ions S^{q+} instead of using SF_6

ARIBE: agreement renewal

To fullfill the next agreement of French Nuclear Safety Agency in **2026**, it is **compulsory** to:

- design a new **safety interlock chain** with modern components
- build a new **shed around the ion source** to have a public area in the whole experimental hall
  $\rightarrow$ campaigns to measure the radiation emitted by the source (Nov/Dec 2023, April 2024)
  $\rightarrow$ design of the new shed for summer 2024
  $\rightarrow$ delivery of the new shed for summer 2025

Acknowledgment

Thanks to all staff