Activities in ARIBE, the low-energy ion beam facility of GANIL

December 2023

Presentation of ARIBE

ARIBE stands for "*Accelérateur pour la Recherche avec les Ions de Basse Énergie*" (in French meaning accelerator for research with low-energy ions). It is the low-energy ion beam facility of GANIL-SPIRAL2 delivering beams of multiply charged ions A^{q+} with a typical energy of $15 \cdot q$keV.

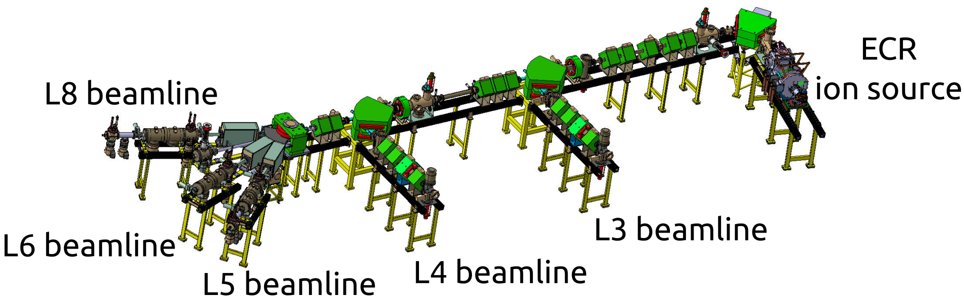

Fig. 1 – Scheme of the ARIBE facility.

Figure 1 displays a scheme of the ARIBE accelerator. It is composed by :
— 1 electron cyclotron resonance (ECR) ion source ;
— 5 beamlines where end-stations can be mounted.

The facility is operated by CIMAP for the access of users to beamtime allocated in the framework of the interdisciplinary program advisory committee (iPAC) through the CIRIL platform. CIMAP staff is also in charge of the usual maintenance of the facility and the support from GANIL staff is punctually granted in case of major breakdown or for specific works for which their expertise is required, e.g. the upgrade of the ion source.

For daily operation, some staff members of CIMAP are qualified to tune the ion beam, this could be done during working hours. After working hours, the facility can run on 24/7 mode if a CIMAP permanent staff member if present to check the operation of the ion source as there is no operator dedicated to the facility.

In the recent years, some major upgrades of the accelerator have been done thanks to fundings granted to GANIL. They were performed by CIMAP technical staff.

Table 1 summarises the beamtime delivered to users during the period 2021–2023. Note that up to 2023, the unit of time in ARIBE was day. From 2024, in order to harmonise the beamtime planning with other GANIL beamlines, the usual UT of 8 hours will be used. Due to 2020 lock-downs, the new control-command systems of the vacuum and of the accelerator ion optics were

	2021	2022	2023
run1	NA	CXLD	NA
run2	24	CXLD	47
run3	42	18	20

Table 1 – Number of UTs delivered to users. Run1 typically covers the March-April period, run2 the May-July period, and run 3 the September-December period. NA means that there was no run planned during the period, CXLD that the run was cancelled.

commissioned during the year 2021 reducing the available beamtime for users. In 2022, the ion source suffered a serious breakdown and new parts were designed, machined and mounted. Therefore no beamtime was available to users during the first semester of 2022.

1 Scientific activities in the period 2021–2023

This sections highlights the main activities of the users during the period 2021–2023.

1.1 Astrophysical ices

In space environments, the synthesis of complex organic molecules (COMs) is possible either by implantation of ions trapped in the strong magnetospheres of giant planets into the icy surfaces of their satellites (e.g. C or S ejected by Io volcanism and impacting Europe), or following radiolysis of small molecules in condensed phase in the ices (H_2O, CO, CH_4, NH_3 etc.). At ARIBE, such processes were studied in recent years with the “space simulator” device IGLIAS (financed by ANR, operational since 2017). Infrared absorption spectroscopy FTIR and mass spectrometry QMS allow *in situ* observation of physico-chemical modifications of the icy layers. *Ex-situ* analysis of residues is performed by e.g. high resolution mass spectrometric methods.

ARIBE is particularly well suited for such studies concerning bodies in the solar system exposed to solar wind, cosmic rays, and magnetospheric ions. Important examples are the satellites Europa and Ganymede of Jupiter, and Titan of Saturn. The implantation of sulfur ions in analogues of Europa surface was used to search for the formation of organics containing sulfur in residues of ice mixtures within a “RIN émergent” project (SCHINOBI) financed by the région Normandie involving PIIM (Marseille), COBRA (Rouen) and CIMAP (Caen). The implantation of oxygen in materials involved use of isotopic oxygen beams to identify chemistry and modifications related to the implanted projectiles (IPAG Grenoble). The Jovian satellites are exposed to an intense flux of sulfur ions ejected into the magnetosphere by the volcanism of Io. Oxygen ions play a particular role for Titan. These studies are in close relation with completed, ongoing or planned space missions like Cassini-Huygens and Galileo (NASA), JUICE (Jupiter Icy Moons Explorer of ESA, launched April 14, 2023) and NASA Europa Clipper (launch in 2024).

Water molecules are omnipresent in space, and other molecules usually are embedded in a water matrix. The question arises if this could lead to reduced radio-resistance, which has been observed for some COMs. Of particular interest are aminoacids like glycine, and aromatic molecules like PAHs (polycyclic aromatic hydrocarbons, e.g. pyrene), and nucleobases. The effects of temperature and concentration need to be quantified. The radiolysis of aromatic molecules in condensed phase and the role of the water matrix in which COMs are usually embedded, were investigated within the TNA of the EU network RADIATE by groups of Center of Education Celso Suckow da Fonseca, CEFET, the Federal University of Rio de

Janeiro (Brasil), and the Astronomical Institute of the Slovak Academy of Sciences (Tatranska Lomnica). Furthermore, within the RIN SCHINOBI, an evaporation device was installed and the amino acid glycine deposited and irradiated for the first time in 2023. These studies are not only pertinent for astrophysics, but also for radiobiology (exposure of living matter to ionizing radiation, cancer treatment) in particular regarding the water environment.

1.2 Molecular clusters

From the last decades, it appears that we are living in a molecular universe with the observation of about 200 molecules in space from the simplest H_2 to fullerenes made up of 60 to 70 carbon atoms. The understanding of the growth mechanism of such complex molecules is of prime importance for the physical chemistry of different astrophysical environment, including the planetary atmospheres such as the one of Titan a moon of Saturn. Therefore, in order to understand the rich molecular inventory, laboratory astrophysics is required to study cold chemical reactions and to simulate the interaction of radiation with the molecular species present in space. Among the radiations, ions show a peculiar interest due their relatively high mass. Thus, in addition to the interaction with the molecular electronic cloud, atomic projectiles could also interact with molecular nuclei in binary collisions.

Using the formation of fullerene as a textbook case, two approaches are considered. On the one hand, in the “bottom-up” one, the typical football carbon cage is made up starting from small carbon molecules. On the other hand, in the “top-down” perspective, a large carbonaceous matter (grains) is physically processed by stellar radiation (photons, electrons, ions). Using the low-energy ion beams delivered by ARIBE, it has been shown that a rich molecular growth could be induced inside of molecular clusters. This approach may be considered as a “middle way” between the “bottom-up” and the “top-down” approaches. Here the cluster acts as a reservoir of matter and a buffer for the energy transfered during the interaction.

Such growth processes have been observed in clusters of polycyclic aromatic hydrocarbons (PAH) and in clusters of fullerenes before 2020. In the last years, different teams (Stockholm University, Sweden ; Lund University, Sweden ; Bar Ilan University, Israel) in collaboration with CIMAP have extended the study of reactivity inside of molecular clusters to different systems showing a wide variety of processes induced by the ion collision. Thus beside the knock-out of atoms (due to binary collisions) playing the pivotal role in the growth observed in polycyclic aromatic hydrocarbons and fullerenes clusters, the electronic excitation and the protonation of molecules inside the clusters are at the origin of the reactivity observed in clusters of small hydrocarbons or amino acids. The reactivity in linear hydrocarbons leads to the formation of carbon cycles while the one in amino acids shows the formation of peptide bonds. Thus the products of the collision of low-energy ions with molecular clusters are relevant in prebiotic chemistry and plays pivotal roles in the emergence of life.

1.3 Commissioning of new devices

The ARIBE facility offers a wide variety of ion beams with a high flexibility in tuning the ion source and accelerator. Therefore users are using the ARIBE facility to commission devices developed in their laboratories. In the last years, different groups used ARIBE beams to develop their new experimental setups.

The FISIC collaboration aims to study the collision between a fast ion and a slow ion. It is led by INSP (Paris, France) and it is gathering about 35 people in France, Germany, Austria, and Argentina. The FISIC crossed beam collision device is under development and is planned to be installed in CRYRING at GSI-FAIR (Darmstadt, Germany). Two experimental campaigns were performed during the 2021–2023 period to commission different elements of the low-energy beamline of FISIC indeed ARIBE delivers similar beams that the one planned in FISIC experiments.

In the last years, another large collaboration used ARIBE beams. This work was led by IPHC (Strasbourg, France) and included GANIL and SIGMAPHY company (Vannes, France). The demonstrator beamline section was developed in Strasbourg then transported and commissioned in September 2021 using different low-energy ion beams delivered by ARIBE facility.

Additionaly, ARIBE was also used to commission a new velocity map imaging spectrometer developed in CIMAP and allowing to measure the momentum of electrons emitted in ion collision. This project was funded by ANR JCJC IMAGERI.

2 Perspectives for the period 2024–2026

Based on the proposals accepted by the iPAC and on the developments under progress, we can foreseen the following activities as the major ones during the next period.

2.1 Astrophysical ices

In the coming years, research in the above described research areas will go on, related proposals were accepted at the 2023 iPAC concerning implantation with sulfur and isotopic oxygen beams and radiolysis of COMs. Also, thanks to the new evaporation device, amino acids and aromatic molecules like nucleobases and PAHs can be deposited *in situ* and be irradiated. A novelty appearing in 2023 and being of importance for future studies is the request for Mg and P beams at ARIBE.

In the next years, a pioneering novel equipment will become available at CIMAP-GANIL : within the PEPR "Origins", a unique multibeam irradiation platform MIRRPLA is under construction. The uniqueness consists in the combination of different types of ionizing radiation (photons, electrons, ions) including the possibility of simultaneous irradiation of samples to study possible synergy effects : for example, ARIBE ion beam plus photons and/or UV electrons to simulate a complex irradiation field as in real space environment. Like IGLIAS, MIRRPLA will be equipped with an infrared spectrometer, QMS and a cold head. In addition, COMs formed during the irradiation and/or heating of ice layers will be detected *in situ* using gas phase chromatography. The MIRRPLA platform will be open to the various scientific communities (astrophysics, radiobiology, environmental and materials sciences) as well as to industry via the GANIL-CIMAP-CIRIL user platform.

2.2 Molecular clusters

Intracluster reactivity induced by ion collisions will continue to be extensively studied in the coming years. The search for peptide bond formation will be extended including looking for some chiral effects in the formation of bonds. Chiral molecules cannot be superimposed with their mirror image like our hands, thus usually one refers to left (L) and right (R) enantiomers. Chirality is pivotal in life, with amino acids being L-chiral in proteins while sugar molecules used in the backbone of DNA are R-chiral. It is believed that such homochirality plays a role in the emergence of life. Any chiral effects will open additional studies using circularly polarised light as available at synchrotron facilities.

Another emerging research field related to reactivity inside of clusters is related to the formation of aerosols and thus atmospheric science. Therefore proposals have been accepted looking for the formation of aerosols particles in ion-clusters collisions. Applications are foreseen to Earth atmosphere but also to other planetary atmospheres such as Titan, Venus, where aerosol particles have been observed. Indeed in Titan atmosphere, low-energy ions from solar winds and from the magnetosphere of Saturn are a source of energy in the atmosphere.

2.3 Molecular physics in model molecules

With the advent of momentum resolved detector of low energy ions and electrons, a comeback of the studies of small model molecular systems, such as N_2, CH_4 C_2H_2, is observed in the proposals accepted during the last iPAC sessions. Low-energy ion collisions offers rather large cross sections for the production of molecular (multi)cations, therefore using the available end-stations equipped with position sensitive detectors, e.g. it is possible to finely study the dissociation dynamics of the molecular cations and to compare measured kinetic energies with predictions of theoretical models.

2.4 Development of the ARIBE facility

As presented before the ARIBE facility is the perfect place to simulate the interaction of ions typical of solar winds and giant planet magnetospheres. It offers a wide variety of multiply charged ions and a flexibility allowing to study different ion interactions during a single beamtime session as tuning the ion source and the accelerator is possible in less than one UT.

Besides the usual light ions, other ions are also observed in space and in the low-energy collision regime their charge state and their masses play an important role in the interaction. Moreover the implantation of reactive species could not be addressed using inert gas ions. Thus using the usual ions delivered by an ion source, such as He^{q+}, O^{q+}, Ar^{q+}, is simply mimicking the interaction of some ions of astrophysical interest such as Mg^{q+}, Si^{q+}, P^{q+}, Fe^{q+}. Therefore, the development of new ion beams using the so-called Metal Ions from Volatile Compounds technique (MIVOC) is required. This may also to deliver sulfur ion beams as one needs to avoid the use of SF_6 gas in the future.

To effectively simulate astrophysical ions, lower ion energies are also required. In 2021, a collaboration gathering GANIL, CIMAP, and the Institute of Applied Physics of the Russian Academy of Sciences (Nizhny Novgorod, Russian Federation) designed a new extraction optics for the ARIBE ion source allowing to efficiently deliver ion beams with extraction voltages as low as few hundreds of eV. Following the simulations, a Memorandum of Understanding was prepared in order to continue the study from an experimental point of view with the mechanical design and machining of the electrodes and test measurements with the new extraction optics. The MoU was ready at the beginning of the year 2022 but the invasion of Ukraine stopped the process.

Finally, the renewal of the agreement of the French nuclear safety agency needs to be done in 2026. According to the last agreement and to new regulations, two major works are foreseen in the next period. On the one hand, the safety interlock chain needs to be renewed. This work will require the expertise of GANIL staff and can be done in collaboration with CIMAP staff. On the other hand, the new regulation requires a public area around the ion source. The current shed does not allow such classification and a new one needs to be designed to comply with radiation protection. In November 2023, a campaign of three weeks of radiation measurement was done in the perspective to establish the specifications of the new shed. This work is done in collaboration with GANIL and CIMAP staff.