Interdisciplinary research in Laboratory Astrophysics:
studies of irradiation effects on molecular ices in different space environments

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Importance and uniqueness of the GANIL facility

Ices, mainly composed of simple molecules such as H_2O, CO, CO_2, NH_3 and others are ubiquitous in space: they are present in comets, satellites of planets (e.g Jovian moons) and on the grains of the dense molecular clouds in the Inter Stellar Medium (ISM). They are constantly exposed to complex and diverse radiation fields due to interactions with solar/stellar winds, magnetospheres or/and cosmic rays (UV, X-rays, electrons, H, He and heavier ions).

Since several decades, laboratory studies are performed extensively to investigate energetic processing of astrophysical ice analogues. However, for a long time, those investigations were mainly focused to evaluate effects induced by weakly ionizing radiation such as UV photons and keV-MeV light ions (H, He) thanks to the use of relatively small and more common keV to MeV proton accelerators. Large scale installations, such as GANIL, open a new energetic window to simulate interaction with swift heavy ions from Galactic Cosmic Rays. Such studies extend the domain of the ion-matter interaction applied to astrophysical contexts.

Since more than ten years, several beam lines of GANIL (IRRSUD, SME and LISE) were used to simulate the interaction of cosmic rays with ices. Some specific heavy ion effects due to the high energy deposition, e.g. concerning sputtering and fragmentation, were found to be of great importance. This energetical domain extends that of weakly ionizing radiation triggering a growing interest in the astrophysical community.

The radiolysis (fragmentation/destruction of molecules) of molecular ices leads to formation of new molecular species including complex organic molecules. The origin of primitive organic matter is a central issue of modern astrophysics. Organic matter precursors are observed in dense ISM phases. These molecules are injected in protoplanetary disks and evolved under radiations (UV, X-rays and ions) in their cold and dense phases. Primitive organic molecules are also constantly formed at the surface of small bodies (asteroids and comets). These different organics components are constantly transported from interplanetary space to planets via e.g. micrometeorites and carbonaceous meteorites. Therefore, these primitive organics molecules contributed to the building blocks of prebiotic molecules on the young Earth. Thanks to state-of-the-art equipment developed at CIMAP in collaboration with the community and financed by various funding sources (including ANR, FEDER), chemical or physical evolution during irradiations can be followed in situ with analytical facilities including Fourier Transform Infrared Spectroscopy (FTIR),visible-ultraviolet spectroscopy (Vis-UV) and mass spectrometry. The instrumental facilities developed on GANIL beamlines is highly competitive providing dedicated apparatus for such inter-disciplinary research on heavy ion large scale accelerators.

A further important and unique feature of GANIL is the possibility to perform experiments on different beamlines covering several regimes of microscopic energy deposition mechanisms, from elastic collisions to electronic excitation, including regimes were both come into play, allowing to mimic effects by ion collisions in different astrophysical environments (evaluation of surfaces in Solar System icy objects, molecular clouds, …). This allows to establish scaling laws for different processes (e.g. sputtering, amorphisation, compaction, fragmentation) and in turn to estimate times scales for compaction and amorphisation, desorption/sputtering rates, and molecular survival times in space.

It is worth to underline, that more than 60 papers in refereed journals have been published and numerous invited talks in prestigious conferences covering atomic and molecular physics and astrophysics such as ICPEAC, HCI, ECLA, ICACS, SHIM, IAU (to name only a few) have been given, resulting from ion irradiation of astrophycial ices studies at GANIL from 2009 to 2020. Since the first exploratory experiments in 2008, the number of users has strongly increased.

Future needs and evolutions

The key facilities for our research in the domain of Laboratory Astrophysics and Astrobiology are and remain the ECR sources and in particular the cyclotron ion beams with their corresponding beamlines ARIBE (ECR Hall D), IRRSUD (C0), SME (CSS1) and HE (CSS2) and the available in situ experimental set-ups which can be used at the different beamlines.

The large demand (a third of the proposals made at last IPAC came from our international community alone) for beam time clearly points out the need for sufficient available beam time. In the future, it could be interesting to advance toward studying mixed radiation fields as in space searching for synergy effects. It would be interesting to add UV, x-ray, and electron radiation sources.

Furthermore, to simulate the complete cosmic ray fields, simultaneous or subsequent irradiation with proton beams would be a major unique advancement to expand the possibilities of the future GANIL. Within the EMIR network, a proposal was made to add a H/He accelerator with the possibility of dual beam irradiation. One could also think about dedicated space irradiation simulation beam line(s) for our community.

Through laboratory simulations of expected radiation effects in icy space environments, showing how to detect them and what observations to search for, the GANIL beam line facilities could significantly contribute to prepare future space missions like the ESA JUICE or the NASA Europa Clipper (exploration of the jovian moons) as well as to interpret the future data for which the GANIL has a unique position in the international community. The experiments performed at GANIL are essential to predict and interpret the observations by such space probes, and also of telescope based observations from the ground (VLT on KBO's). There will be also relevant for the future space telescope JWST in which ESA and European scientists are engaged. Some of the involved PIs are already performing prospective experiments at GANIL.