Interdisciplinary research: Material Science (inorganic)

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The use of beams of energetic heavy ions is a truly unique tool for the study of inorganic solids, that will, in decades to come, continue to have a distinct impact on both fundamental solid state physics and materials science, as well as on more applied aspects. The use of controlled damage induced by ion irradiation is and will continue to be a very original and ever more refined tool for the control of a host of physical properties on the nanometric scale. In particular, it is foreseen that the development of nanobeams and irradiation by single ions at a time will take a flight.

GANIL's ion beams provide an unrivaled laboratory to simulate the irradiation conditions and therefore the aging conditions of materials in nuclear reactors, in accelerators, in outer space, in defense, and in other situations where materials are exposed to extreme conditions. What is essential for any application is the consequences of the irradiation-induced structural modifications on the functional properties (electrical, mechanical, chemical…) of the materials. Therefore, there is a crucial need for the development of a multiscale predictive approach to better understand the irradiation effects induced in materials and even to predict those. As a consequence, the material science community working at GANIL has developed a host of in-beam analysis devices coupled to advanced *ex-situ* techniques to improve the understanding of the long-term evolutions of material properties under irradiation. With the community of researchers worldwide, we hope to have the possibility to continue paving the way toward this direction in the future.

In addition to experimental data, computational works have provided significant results. For instance, recent progresses in numerical simulations have allowed, by adding the energy profile on lattice to molecular dynamics cells, to couple both electronic excitation effects and displacement cascades induced by ballistic collisions. These theoretical works aim at understanding the joint effect of electronic and nuclear energy losses of the projectiles slowing down in the matter. These processes can be additive, resulting in an enhanced disordering, they can act one against the other, leading to the annealing, by electronic excitations, of the ballistically-induced defects; or they can combine in synergy (huge increase of the number of defect created by ballistic collision due to electronic excitations) as recently highlighted in III-N semiconductors. Further experimental studies are thus still needed to better understand and simulate irradiation effects in a broad variety of materials. In particular, analyzing the consequences of the slowing-down mechanisms on the atomic diffusion in ceramics may be crucial for determining the long term evolution of material microstructures; which is still poorly modeled in non-metallic materials.

A major issue is the resistance to radiation damage of novel types of materials, or parts made using new manufacturing and assembly techniques. A first avenue in the realm of new materials concerns the highly refractory high entropy alloys as well as of metallic glasses, the mechanical properties of which can actually enhanced using irradiation. New processes notably include 3D printing used for the manufacturing of complex mechanical (spare) parts for the nuclear industry. As the microstructure resulting from the 3D printing process is quite different from that known for the bulk (in terms of grain size, texture, porosity) and the initial state is far from equilibrium, prior thorough studies of the 3D-printed material's behavior under irradiation are mandatory.

A new separation/conditioning strategy for the treatment of radioactive effluents is based on the use of porous functionalized supports, *i.e.* mesoporous silicas. The mesoporous matrix act first as a filter for the separation of the radionuclides, whence, after a porosity collapse due to self-irradiation by short-life actinides, they act as an encapsulation matrix. The study of the porosity closure mechanism and kinetics is performed using GANIL ion beams during simulation irradiations. In the same context, ongoing research on porous Metal-Organic Framework (MOFs), initially oriented towards catalysis, gas storage, optics or medicine, is gaining interest in the nuclear power industry. Through their original chemistry and exceptional porosity, these materials are anticipated as immobilization matrices through the capture and sequestration of radioactive gas (I, CH_3I, Xe, Kr) or dissolved actinides in the event of a serious nuclear accident. A perfect knowledge of their behavior under alpha irradiations, as well as the evolution of the efficiency of the associated processes, is the very first step for such applications. It is worth recalling that, provided an ingenious choice of ion and energy, GANIL ion beams have been used for close to 20 years to simulate α particle irradiations in organic materials.

As for spatial applications, a major application is the development and radiation hardness of new generations of solar cells or electronic devices. Such semiconductor-based devices have to be carefully engineered for the conditions of low temperature and low illumination in which they are to function, and at the same time resist the radiation damage by cosmic radiation, the effect of which on their electronic properties can be very severe. Heavy ions of tunable energy can realistically mimic a wide range of incident radiation in the interplanetary environment.

A field for which GANIL beams are frequently used is defect engineering or, more generally, the use of swift heavy ions to modify materials in a beneficial (and controlled) way. For example, the sensitivity of semiconducting materials to radiation damage through modification of the carrier density and mobility induced by the incorporation of irradiation induced point defects that can be so harmful to on-board instrumentation, can be put to an advantage using so-called “Fermi-level engineering”. Irradiation can be used a particularly fine tool to adjust the electronic properties in such a way that particular features of a material – such as the peculiar surface states in topological insulators or the defect level population in large gap materials for spectroscopic applications – can be enhanced in a scientifically or technologically useful way. The tuning of the carrier density can be further used for inducing electronic phase transitions such as in, e.g. Mott insulators.

The use of ionic nano-beams or even irradiation with single ions can take defect engineering yet one step further. For example, fashioning of single defects in nano-scale wide bandgap materials is extremely useful for designing ultimate sensors for optical, electrical, and magnetic spectroscopies, as well as for magnetic imaging. The seminal example is the controlled introduction of NV centers in diamond; however, given the huge wealth of materials potentially hosting useable and controllable defects in the middle of the band gap, the field is still to be considered in its infancy.

Not unrelated is the use of ion-induced damage for the study of local configurations and the local environment in insulating glasses. These can be studied through spectroscopic means.

The use for heavy ion irradiation for the introduction of controlled disorder in magnets, superconductors, and other quantum materials will continue to be a tool of choice for the exploration of both fundamental properties and limits to applications. Ion-induced latent tracks have the geometry and dimensions that ensures an optimal interaction with superconducting vortex lines as well as with elastic, electric, and magnetic domain walls in high-anisotropy materials, as well as with topological objects such as skyrmions, and have and will continue to be used in creative manners to pin or manipulate these objects. Beyond this, ion beams will be used as a method to controllably introduce disorder in quantum materials of many different kinds as a means to test the robustness of quantum ground states, as well as to controllably induce phase change.

Phase change and ion-beam is also a topic of great interest for the enhancement of nanocrystals for applications. In particular, modification of the structure and the modulation of the local composition can be achieved. Ion-beam shaping is a useful tool to fashion nanoscale particles of given size and shape for, e.g. plasmonic applications.

In the very active and promising realm of low-dimensional materials, which includes, apart from the carbon-based materials and the dichalcogenides, the nearly infinite variety of hetero-structures of different kinds and properties, including Moiré-type hetero-structures, ion-irradiation damage can be used to tune local electronic and mechanical properties, but also as a calibrated tool to induce nano-scale apertures or disorder.

Advantages of GANIL and requirements for interdisciplinary research in inorganic materials

The GANIL facility delivers a beam offer that is unique in the world, with a wide choice of ions and energies, thus allowing the variation of the linear energy transfer and the electronic to nuclear stopping power ratio. This variety and versatility of the ion beam is obviously a chance for our community. In our fields we usually need, for each experiment, several beam times (between 1 UT and, at maximum, 10 UT, with a mode of around 3 UT), ideally exploiting different ion beams or under different conditions (temperature for instance). That is why it is important to have several runs per year in order to optimize the research programs on a reasonable time, which is crucial for PhD student in particular.

One of the major strengths of GANIL is the development of many unique (or near-unique) online experimental set-ups. The CIRIL platform develops instruments for the entire community, a prime example being the special chamber devoted to uranium irradiation at the IRRSUD beamline. This dedicated chamber is only useful for the external teams exploiting it, but many other in-line equipments developed at CIMAP such as X-ray diffraction, optical absorption, infra-red spectroscopy, cryostats, and ovens are open for the use by the community at large. External user set-ups can also be adapted to the lines by the CIRIL staff.

To maintain the scientific dynamic of research at GANIL, the role is of the EMIR community in constantly defining new experimental developments in close collaboration with CIMAP researchers cannot be insufficiently emphasized. Some very important recent developments (SPORT for time-resolved iono-luminescence, PELIICAEN for controlled ion implantation and characterizations) are under commissioning and others are under study. For instance, EPR (Electronic Paramagnetic Resonance) spectroscopy would be particularly useful for the study of metal complexes and to gain a better understanding of the formation and the reaction of intermediate species under irradiation. Raman spectroscopy could be developed in-beam for long-range order analysis with depth resolved characteristic, or for organic materials irradiations in aqueous atmosphere. In the EMIR network, we have also pointed out that it would be very interesting to expand the possibilities of beams at GANIL by adding an accelerator with an intermediate energy range, straddling that of ARIBE and IRRSUD, with the possibility of *in-situ* RBS measurements and dual beam irradiation coupling the “low” and “high” energy beam line, i.e. playing on the synergistic combination of electronic and nuclear stopping powers.

The community will of course remain attentive, as it has always been, to the new possibilities to be offered by the new development of GANIL and SPIRAL2. To name a few, we shall follow opportunities to irradiate metallic materials at NFS with H, He (20-40MeV/A) for nuclear applications or to use neutron fluxes produced by NFS to analyze materials irradiated at GANIL by neutron diffraction or even to develop beta-NMR at DESIR for the study of local electronic and magnetic properties of irradiated superconductors.