**Contribution aux exercices de prospective 2020-2030**

***Contribution to the 2020-2030 prospective reflection***

**Energie nucléaire et environnement**

*Nuclear energy and environment*

**1) Aperçu / *Overview***

**Thème de recherche proposé** : *Research topic of the proposition :*

Matériaux et Faisceaux d’ions *Materials and Ion Beams*

**Axe principal concerné** : *Main research topic*(voir la liste des thèmes en fin de document) : Irradiation des matériaux nucléaires *Irradiation of nuclear materials*

**Contributeur(s) (et affiliations) de la proposition** : *Proposition’s author(s) and affiliations :*

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**Résumé** (500 caractères max., incluant les espaces) : *Summary (500 characters maximum, including spaces) :*

A pertinent application of ion beams is the simulation of radiation effects in materials submitted to severe radiative environments, concerning the qualification of matrices used for the confinement and/or transmutation of nuclear waste (fission products, minor actinides), and the evaluation of structural materials for future nuclear reactors (fission and fusion). Ion beams could also be used to synthesize new materials or to modify the properties of materials, either from a fundamental viewpoint or for technological applications.

**2) Description de la question/problématique scientifique rattachée au thème (1 page) / *Description of the scientific issue connected to the topic (1 page)***

Merci d’indiquer le positionnement des objectifs dans l’état de l’art (échelle internationale), les liens avec des projets existants et/ou futurs, la pertinence du cadre académique dans la question abordée. *Please include description of motivation against (international) state-of-the-art, as well as links to other projects (existing or foreseen), relevance of the academic frame for the issue suggested.*

Ion beams may be implemented for technological applications in many domains such as Physics, Chemistry, Electronics, Medicine, Earth and Environmental Sciences. A pertinent application of ion beams is the **simulation of radiation effects in materials** submitted to severe radiative environments. This topic concerns the qualification of matrices used for the confinement and/or transmutation of nuclear wastes (fission products, plutonium, minor actinides), and the evaluation of structure materials for nuclear reactors of the next generations (fission and fusion). Such experiments are based on the possibility to use ions of various masses at energies ranging from a few tens of keV up to a few hundreds of MeV, covering thus a broad stopping power range. They allow the simulation of radiation effects due to the uranium fission by using swift heavy ions, or the disintegration of actinides by using low energy heavy ions and MeV alpha particles. Another item concerns **nuclear microanalysis techniques** using low-energy ion accelerators (e.g. Ion Beam Analysis, such as RBS). These non-destructive techniques provide quantitative analyses of the elements located in the surface layer of a solid and give information on their depth distribution with a resolution of the order of a few tens of nanometres. Low energy ion beams are also used for **ion beam synthesis** of out-of-equilibrium materials: ions are incorporated into a solid matrix and a subsequent thermal annealing usually favours the formation of nano-precipitates following the typical ion beam synthesis scheme. A last item is using **ion beams to modify the properties of materials**, either from a fundamental point of view or for technological applications, such as in the field of energy production. For all these points we have an extensive use of the SCALP ion accelerator facility located at CSNSM, and especially the JANNuS-Orsay part, that consists in coupling a transmission electron microscope (TEM) to two ion accelerators, allowing *in situ* observation of single/dual ion beam effects in a solid material.

Several scientific activities are based on the use of ion beams for studies related to Solid State Chemistry and Physics according to the aspects described above. The following fields (detailed in next part) are mainly concerned for the near future:

- Fundamental studies and modelling on particle-solid interactions,

- Radiation effects in oxides and carbides (fuels, confinement and/or transmutation of radioactive waste),

- Behaviour of steels and semi-conductors under ion irradiation and gas presence (structural materials for current and future fission and fusion reactors),

- Ion beam synthesis of nano-oxide in steel.

**Collaborateurs (personnes ou organismes) identifiés ou potentiels (dans et hors IN2P3)** : *Identified of potential collaborators (people or organizations, in- and outside IN2P3) :*

Dans l’IN2P3 :

Équipe Radiochimie, IPN, Orsay

IP2I, Lyon

CENBG, Bordeaux

En dehors de l’IN2P3 :

GEOPS Orsay, CEA Saclay (DEN/DMN/SRMP et SRMA), CEA Cadarache (DEN), CEA Marcoule (DEN), ICSM Marcoule, IRCER Limoges, CEMHTI Orléans, CIMAP Caen, Pprime Poitiers, GPM Rouen, IM2NP Marseille

+ coll. Internationales

NCBJ Warsaw, ITU Karsruhe, MEPhI Moscow, the University of Tennessee, Oak Ridge National Laboratory

**Instruments/Outils impliqués :** *Facilities/tools involved :* plateformes JANNuS-Orsay/SCALP (CSNSM), JANNuS-Saclay (CEA), PIAGARA (CENBG), GANIL (SME et IRRSUD, CIMAP), Fédération EMIR, Fédération METSA, Réseau RENATECH, … etc

**3) Suggestion de projet(s) pouvant répondre à la question/problématique proposée (1 page max.) / *Suggestion of project(s) addressing the issue proposed (1 page max)***

Below are detailed the different projects we propose to study in the near future:

- **Fundamental studies and modelling on particle-solid interactions:** Ion/solid interactions applied to materials science represent a vast research field in which some basic questions remain to be elucidated. One typical example is the effect of combined electronic and nuclear energy deposition on the atomic network of materials that can be investigated using dual beam irradiation. Besides, tools and models for quantitative description of the radiation-induced effects, involving both experiments and atomistic simulation, are required and are thus being developed.

- **Radiation effects in oxides and carbides (fuels, confinement and/or transmutation of radioactive waste)**: The radiation tolerance of nuclear fuels and a full understanding of the (micro)structural evolution in standard or accidental condition is a major challenge. Binary metal oxides possessing the fluorite-type structure are well known to be radiation tolerant materials. Today’s fuel UO2 does not become amorphous under irradiation but exhibits instead a defective structure, whose specific microstructure depends on several parameters, such as the burnup, local temperature of the fuel, irradiation conditions, presence of incorporated impurities (e.g. fission products, transuranium elements). Although the basic mechanisms of defects production in irradiated solids are well established, considerable experimental and computational efforts are undertaken to better understand the exact role played by the various relevant parameters in the formation of a specific microstructure and on the final destabilisation of the solid. The role played by the final microstructure of the nuclear fuels on the fuel dissolution machanisms is also of prime importance for reprocessing processes (e.g. multi-recycling of Pu) or direct storage in a geological site. Beside fuels radiation damage in immobilization matrices for high level wastes, such as phosphate-based matrices (apatite, monazite) deserves also current efforts.

- **Behaviour of steels and semi-conductors under ion irradiation and gas presence (structural materials for current and future fission and fusion reactors)**: Extending further the life of existing pressurised water nuclear reactors is a major challenge that would enable to save tens of millions of euros per year. The safety of the system must however be preserved, which requires a very good knowledge and a good control of the mechanisms of ageing of the constitutive materials. Inside the reactor vessel, the baffle bolts, made of austenitic stainless steels, are particularly important to maintain the mechanical integrity of the system. They are subjected to intense neutron irradiation at elevated temperature. In these conditions, the defects created by irradiation as well as the He and H gas produced by nuclear reactions are likely to induce drastic changes detrimental to the stability of the material, among which a phenomenon of swelling. Studying the evolution of austenitic steels microstructure under irradiation and gas presence is therefore of importance. Moreover ferritic-martensitic steels (reinforced or not by an oxide dispersion, called ODS) are excellent potential candidates for Generation IV fission and fusion reactors. The understanding of elementary radiation damage mechanisms (primary dislocation loops, role of alloying elements, accumulation of gas, role of matrix-interface precipitate) is essential and is currently being studied. Finally, semiconductors (such as AlN) seem good candidates for fusion applications although a detailed understanding of their behaviour under irradiation and gas presence is required.

- **Ion beam synthesis of nano-oxide in steel**: ODS (Oxide Dispersed Strengthened) steels reinforced with metal dispersions of nano-oxides are promising structural materials for future nuclear reactors. The detailed understanding of the mechanisms involved in the precipitation of these nano-oxides would improve manufacturing and mechanical properties of these ODS steels, with a strong economic impact for their industrialization. A perfect tool to experimentally study these mechanisms is ion implantation, which nicely reproduces many key aspects of the microstructural processes involved in conventional powder metallurgy-based technique of ODS steel production, and where the various parameters of precipitate synthesis are under control.

*Indiquer si possible l’envergure qu’auraient ce ou ces projets (manpower, budget, durée).*

*Indicate if possible the scale of this(these) project(s) (manpower, budget, duration).*

These projects could be detailed as in the table below, in terms of manpower, budget and duration. Please note that PhD students and post-doctoral researcher salaries have to be added for each (sub-)project.

|  |  |  |  |
| --- | --- | --- | --- |
| Project | Average manpower (per year) | Minimum budget per year (without salaries, only running costs) | Foreseen duration |
| Fundamental studies and modelling on particle-solid interactions | 30 pers.mois | 15 k€ | > 10 years |
| Radiation effects in oxides and carbides (fuels, confinement and/or transmutation of radioactive waste): | 60 pers.mois | 20 k€ | > 10 years |
| Behaviour of steels and semi-conductors under ion irradiation and gas presence | 60 pers.mois | 20 k€ | > 10 years |
| Ion beam synthesis of nano-oxide in steel | 30 pers.mois | 10 k€ | 5 years |

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**Merci de renvoyer ce document à** [**prosp2020-GT11-copil-l@in2p3.fr**](mailto:prosp2020-GT11-copil-l@in2p3.fr) **avant le   
1er Novembre 2019**

***Please send this document to*** [***prosp2020-GT11-copil-l@in2p3.fr***](mailto:prosp2020-GT11-copil-l@in2p3.fr) ***before   
November 1rst, 2019***

**Liste des thèmes**

* Physique des réacteurs : modélisation et expérimentation, neutronique, thermohydraulique, couplage multi-physique, acquisition de données de base (sections efficaces, évaluation des données nucléaires, données de thermohydraulique), physique de la sous-criticité, études de scénarios, ouverture interdisciplinaire : approche technico-socio-économique (prix, coût, ressources, ...). Application aux réacteurs actuels et innovants, études de scénarios...
* Radiochimie des matières nucléaires : données de base (spéciation, interaction avec ligands), compréhension des processus de dissolution, de séparation, processus de diffusion, modélisation. Application au traitement des combustibles usés, processus de dissolution et d'extraction, conditionnement des radionucléides, diffusion des radionucléides dans un site de stockage (matériaux, barrière, argile)...
* Irradiation des matériaux nucléaires : compréhension des processus d'endommagement par les ions et neutrons, acquisition de données de base, modélisation. Application aux matériaux de structures et combustible, tenue des déchets nucléaires à l'irradiation, impact de l'irradiation dans les gisements...
* Radioactivité et environnement : acquisition de données de base (spéciation, ligands), modélisation, processus de transferts, mesures de très basses radioactivités. Application au comportement des radionucléides dans le biotope, microorganismes, exploration de procédés de remédiation.

***Research topics :***

* Reactor physics : modelling and experimentation, neutronics, thermohydraulics, multi-physics coupling, basic data acquisition (cross sections, evaluation of nuclear data, thermohydraulics data), subcriticality physics, scenario studies, interdisciplinary activities : technical-socio-economic approach (price, cost, resources, etc.). Application to current and innovative reactors, scenario studies....
* Radiochemistry of nuclear materials : basic data (speciation, interaction with ligands), understanding of dissolution, separation, diffusion processes, modelling. Application to the treatment of spent fuels, dissolution and extraction processes, conditioning of radionuclides, diffusion of radionuclides in a storage site (materials, barrier, clay)...
* Irradiation of nuclear materials : understanding of ion and neutron damage processes, basic data acquisition, modelling. Application to structural and fuel materials, resistance of nuclear waste to irradiation, impact of irradiation in deposits...
* Radioactivity and environment : acquisition of basic data (speciation, ligands), modelling, transfer processes, measurements of very low radioactivity. Application to the behaviour of radionuclides in the biotope, microorganisms, exploration of remediation processes.