CIRIL: more than 30 years of interdisciplinary research at GANIL

The CIRIL: 30 years of interdisciplinary research at GANIL meeting was held in Caen, France, in October 2013. The meeting provided an excellent opportunity to present the research performed with ion beams delivered by the GANIL facility (Grand Accélérateur National d’Ions Lourds, Caen, France). This proceedings volume comprises a series of reviews from different disciplines (physics, chemistry, biology, medicine, etc) of the results obtained with GANIL ion beams. Unfortunately, the issue is missing two major research domains concerning the induced damage in metals and insulators. Therefore, we refer the interested readers to the following publications: metals\(^1\) and insulators\(^2\).

**Early non-nuclear experiments at GANIL**

Over 30 years, the small pioneering team who created CIRIL (Centre for Interdisciplinary Research with Heavy Ions) has evolved into a laboratory of over 100 people, and has acquired an international reputation. The 30 years of partnership with GANIL has greatly helped the development of instrumentation dedicated to interdisciplinary research. Over this time, service to external users has remained the priority for the CIRIL–CIMAP (Centre de Recherche sur les Ions, les Matériaux et la Photonique). Technicians, engineers and researchers devote a significant part of their time to this activity and have developed instruments that are readily available to external users.

In the 1980s, two people, Jean-Pierre Briand and Yves Quéré, played an important role in the creation of a research activity in areas other than nuclear physics at GANIL: the physics of atomic collisions and the study of materials under radiation. In order to fully reach its community, they suggested that CIRIL would be independent in the research themes that it develops and supports, while remaining dependent on its GANIL collaboration to access the ion beam. This original situation has actually allowed the expansion of this research activity, although its benefits had to be underlined every time GANIL underwent a change of director. Still, we must recognize that all GANIL directors have embraced this situation, and most have understood the importance of the presence of CIRIL for the development of interdisciplinary research at GANIL. With their help, we have been able to implement investments for our communities.

\(^1\) Dunlop A and Lesueur D 1993 Damage creation via electronic excitations in metallic targets. I. Experimental results *Rad. Eff. Def. Sol.* **126** 123

\(^2\) Toulemonde M, Bouffard S and Studer F, Swift heavy ions in insulating and conducting oxides: tracks and physical properties 1994 *Nucl. Instrum. Methods B* **91** 1
Figure 1: Mounting of the first atomic physics experiment on the LISE line in 1983.

One beneficial effect of CIRIL concerns the cross-fertilization of the two communities: physics of atomic collisions, and material irradiation, which previously had few opportunities to collaborate. The oral presentations of the experiment proposals at the Interdisciplinary Program Advisory Committee (iPAC) have led to better reciprocal understanding and teamwork.

In the beginning, the interdisciplinary research had access to only two equipments: IRABAT in room D5 and LISE (Ligne d’Ions Super-Epluchés) (D3–D4). IRABAT (the acronym meaning irradiation at low temperature) is a device in which the samples can be irradiated with online control of the ion flux and of its homogeneity. The material temperature can be tuned from 4 K to a few hundred °C. This equipment has been thoroughly renovated and is still operational in the D1 room. It has inspired several foreign accelerator facilities’ own irradiation devices. For atomic physics, LISE is an achromatic line in which highly charged ions can be produced and used for spectroscopy experiments in gas or solid phases. This equipment, shared by the nuclear and atomic physicists, has been widely used for the study of collisional processes for more than fifteen years. The line was subsequently completely adapted for research on exotic ions and is now rarely used by our community.

At the beginning of CIRIL, systematic studies of defect production by GeV ions were undertaken at GANIL in a very large class of materials. These pioneering works gave many breakthrough results: for example, the effects of electronic excitation has been undoubtedly shown in metals and in amorphous metallic alloys and the evolution of the track morphology described by means of several technical measurements used concomitantly. It is impossible to be exhaustive: in many other materials, particularly fruitful results were published for polymers, silica and others.

3 Jousset J C, Irradiation facilities at GANIL (Grand Accélérateur National d'Ions Lourds) 1984 Ann. Chim. Sci. Mat. 9 373-376
4 Remilleux J, Studies of non-nuclear physics at GANIL 1988 Nucl. Instrum. Methods B 33 851-856
5 Dunlop A, Lesueur D, Morillo J, Dural J, Spohr R, and Vetter J, A new damage mechanism in a crystalline metallic target irradiated with heavy giga-electronvolts ions 1989 C. R. Acad. Sci. 309 1277-1282
6 Audouard A, Balanzat E, Fuchs G, Jousset J C, Lesueur D, and Thomé L, High-energy heavy-ion irradiations of Fe85B15 amorphous alloy: evidence for electronic energy loss effect 1987 Europhys. Lett. 3 327-331
7 Rizza; G From ion-hammering to ion-shaping: an historical overview 2015 present issue
8 Studer F, Groult D, Nguyen N, and Toulemonde M, Threshold electronic energy loss for the creation of latent tracks in Y3Fe5O12 and BaFe12O19 oxides irradiated by high energy heavy ions 1987 Nucl. Instrum. Meth. B 19-20 856-859
9 Houpert C, Studer F, Groult D, and Toulemonde M, Transition from localized defects to continuous latent tracks in magnetic insulators by high energy heavy ions: a HREM investigation 1989 Nucl. Instrum. Meth. B 39 720-723
10 Le Moël A, Duraud J P, and Balanzat E, Modifications of polyvinylidene fluoride (PVDF) under high energy heavy ion, X-ray and electron irradiation studied by X-ray photoelectron spectroscopy 1986 Nucl. Instrum. Meth. B 18 59-63
11 Ngonov-Ravache Y, Spectroscopic study of chemical modifications induced by swift heavy ions on polymers: the contribution of the CIRIL Platform and the CIMAP laboratory 2015 present issue
12 Dooryhee E, Langevin Y, Borg J, Duraud J P, and Balanzat E, Formation of paramagnetic defects in high-purity silica by high-energy ions 1988 J. Appl. Phys. 63 1399-1407
At the same time, the beam-foil spectroscopies were implemented on LISE for the measurement of Lamb shift on hydrogen- or helium-like ions for QED theory testing\textsuperscript{13} and, in the UV domain, atomic transitions were measured\textsuperscript{14}. The experiments on charge exchange in solids led to a convincing description of the atomic processes during swift-ion flight in solids\textsuperscript{15,16,17}. Taking advantage of the unique optical quality of the LISE line, experiments performed in channelling conditions have, for example, demonstrated the possibility of freezing the initial charge state for the well-channeled ions\textsuperscript{18,19}. The experiments on beam-gas collision and recoil-ion spectroscopy, begun in the mid-1980s, will essentially continue with medium-energy and multi-charged low-energy ions\textsuperscript{20,21,22}.

**Opportunities offered by GANIL**

The years from 1983 to 1989 were years of increasing power as shown in figure 2. The number of external users gradually grew to 200 per year.

![Figure 2: Number of external researchers using one of the GANIL lines since the creation of CIRIL (a user who comes twice a year is counted twice).](image)

In 1989, major construction of the medium-energy line (SME) renewed the interdisciplinary research. Indeed, this SME line (in room D1) allows the addition of about 3000 hours of beam time for material irradiation and collision physics to the 10% of high-energy beam time. Simultaneously, IRABAT was transferred to room D1. The number of users then increased to around 300 (typically 100 different researchers coming about three times a year). Neglecting fluctuation, the annual user number has remained nearly constant for more than 20 years.

\textsuperscript{13}Tavernier M, Briand J P, Indelicato P, Liesen D, and Richard P, Measurement of the (1s) Lamb shift of hydrogen-like krypton 1985 J. Phys. B 18 L327-330
\textsuperscript{14}Martin S, Buchet J P, Buchet-Poulizac M C, Denis A, Desesquelles J, Druetta M, Grandin J P, Henneacket D, Husson X, and Lecler D, Observation of the resonant lines $2s_{1/2}^2p_{3/2,1/2}$ of lithium-like xenon 1988 Nucl. Instrum. Meth. B 31 79-81
\textsuperscript{15}Rozet J P, Chetioui A, Nicolai P, Chabot M, Politis M F, Touati A, Vernhet D, Wohrer K, Stéphan C, and Grandin J P, Evolution of fine structure populations as a test of solid target effects 1991 Z. Physik D 21 5331-5332
\textsuperscript{16}Lamour E, Gervais B, Rozet J P, and Vernhet D, Production and transport of long-lifetime excited states in pre-equilibrium ion-solid collisions 2006 Phys. Rev. A 73 042715
\textsuperscript{17}Lamour E, Rozet J-P, Vernhet D, Gervais B, Grandin J P, Lelièvre D, Ramillon J-M, Rothard H, Transport of fast excited ions through solids probed by X-ray spectroscopy 2015 present issue
\textsuperscript{18}Cohen C, Dural J, Gaillard M J, Genre R, Grob J J, Hage-Ali M, Kirsch R, L’Hoir A, Mory J, Poizat J C, Quéré Y, Remillieux J, Schmaus D, and Toulemonde M, High-energy heavy ions in crystals in Relativistic Channeling 1987 Plenum, New York, NY, USA, pp. 493-503
\textsuperscript{19}D. Dauvergne, Crystal assisted experiments for multi-disciplinary physics with heavy ion beams at GANIL 2015 present issue
\textsuperscript{20}Grandin J P, Henneacket D, Husson X, Lecler D, Lesteven-Vaissé I, and Lisfi D, Recoil energies of highly charged ions produced in swift ion-atom collisions as deduced from time-of-flight measurements 1988 Europhys. Lett. 6 683-638
\textsuperscript{21}Fléchard X, Adoui L, Ban G, Boduch P, Cassimi A, Chesnel J-Y, Durand D, Frémont F, Guillaud S, Grandin J-P, Henneacket D, Jacquet E, Jardin P, Lamour E, Liénard E, Lelièvre D, Maunoury L, Mery A, Naviliat-Cuncic O, Prigent C, Ramillon J-M, Rangama J, Rozet J-P, Steydtli S, Trassianelli M and Vernhet D, Primary processes: from atoms to diatomic molecules and clusters 2015 present issue
\textsuperscript{22}Zettergren H, Ions interacting with complex molecular systems: the role of a surrounding environment 2015 present issue
Because of the exceptional opportunities offered by GANIL, CIRIL has continued to invest for the benefit of the interdisciplinary research community. First, at very low energy, with multi-charged ions delivered by ECR sources, the LIMBE facility was developed in collaboration with the Atomic Spectroscopy Laboratory, Caen, who joined CIRIL in 1999.\textsuperscript{23} The possibilities, initially limited to two experimental positions, were extended to five stations, with the transfer from Grenoble to Caen of the AIM facility (Multi-charged Ion Accelerator) and the hiring of two new members. The new facility, named ARIBE,\textsuperscript{24} was inaugurated in 2005. ARIBE, associated with the European network of infrastructure ITS-LEIF, has become the mainstay of research on collisions of multiply charged ions with increasingly complex targets (molecules, C\textsubscript{60}, atomic and molecular clusters, surfaces…).

IRR\textsubscript{SU}D (meaning irradiation toward south) line was built in 2004. IRR\textsubscript{SU}D takes advantage of the presence of two compact cyclotrons; however only one is used to inject towards the high-energy acceleration. The ‘free’ cyclotron is used for material irradiation.

Since 2005, CIRIL has therefore experiment stations in all the acceleration steps of the GANIL ions: ARIBE at the ion sources, IRR\textsubscript{SU}D after the first cyclotron (C0), SME after the second cyclotron (CSS1) and D1 at full energy. Thus, in 2013, about 6000 hours of beam time were made available to our community.

Thirty years of evolution of the interdisciplinary research

Obviously, these investments have accompanied or permitted significant changes in research topics. Spectroscopy, which was previously a major activity, disappeared in the early 1990s and was progressively replaced by research on ion--atom collision. Ten years later, with the availability of slow highly-charged ion beams, experiments on the basic processes induced by multiple electron capture on atoms, molecules and clusters have been the focus of most of the research effort. Work in this domain remains active and has led to several outcomes in radiobiology, space chemistry, ion--surface interaction and ion guiding in micro-capillaries. Figure 4 shows these thematic evolutions according to the topic of the experimental proposals.

Similarly, the research on materials under dense electronic excitation can be characterized in different phases (see figure 5). During the earlier periods, the main research effort concerned the description of the morphology of the latent track in insulators, and the study of the effect of electronic excitation on metals and metallic alloys. While the research at GANIL on metallic materials disappeared in the 2000s, research activity on latent tracks in nuclear ceramics continues. The use of ion beams as a tool to understand or control solid state properties has been the subject of many experimental proposals, up to 25% in the first half of the 1990s. Research into high-$T_{c}$

\textsuperscript{23} Maunoury L, Leroy R, Been T, Gaubert G, Guillaume L, Lecler D, Lepoutre A, Mouton P, Pacquet J Y, Ramillon J-M, and Vicquelin R, LIMBE: A new facility for low energy beams 2002 Rev. Sci. Instrum. 73 561-563

\textsuperscript{24} Bernigaud V, Kamalou O, Lawicki A, Capron M, MAisonny R, Manil B, Maunoury L, Rangama J, Rousseau P, Chesnel J-Y, Adoui L, and Huber B A, ARIBE: a low energy ion beam facility in Caen 2008 Publ. Astron. Obs. Belgrade 84 83-86
superconductors and vortex pinning by latent tracks has been particularly active during the past fifteen years, with 230 papers published in relation with an experiment performed at GANIL.

![Figure 4: Evolution of the research into the physics of collisions with the ion beam of GANIL. These curves have been extracted from a compilation of all experimental proposals.](image)

![Figure 5: Evolution of the research into materials under irradiation with the ion beam of GANIL. These curves have been extracted from a compilation of all the experimental proposals.](image)

New scientific communities have also discovered GANIL ions mostly through research where CIRIL played a major role. The organization of the JECR conference (Journées d’Études de la Chimie sous Rayonnement) in Caen in 1994 initiated a series of experiments on chemistry under radiation with an extension to physical chemistry in the space environment. The creation of a radiobiology laboratory (LARIA) jointly by CEA/DSV and CIRIL led to the growth of radiobiology activity with GANIL ions. This laboratory is a key element of the ARCHADE project that proposes to treat cancers by hadron therapy.

In terms of users since the first beam, 70% are external, of which 70% are French. At the beginning of 2014, scientific production was substantial: more than 1400 regular papers were published and 175 PhD students have confirmed work using a GANIL beam. Most noteworthy are the 2150 authors who signed a paper linked to an experiment performed at GANIL.

These proceedings are an opportunity to acknowledge the important contribution of one of CIRIL’s pioneers, Jacques Dural, who unfortunately passed away recently. This book is also dedicated to the.

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26 Boduch P, Dartois E, de Barros A L F, da Silveira E F, Domaracka A, Lv X Y, Palumbo M E, Pilling S, Rothard H, Seperuelo Duarte E and Strazzulla G, Radiation effects in astrophysical ices 2015 present issue
27 Testard I, Radiobiology at GANIL: local project and others fields studied 2003 Les Nouvelles du GANIL 68 8-13
28 Beuve M, Moreau J-M, Rodriguez C and Testa E, Biological systems: from water radiolysis to carbon ion radiotherapy 2015 present issue
memory of Natacha Betz, Gaetano Lanzano and Camille Cohen who have contributed through their beautiful experiments to the success of CIRIL.

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