Atomic Physics with the SPIRAL2 project

27 and 28 March 2008

atomphys.spiral2@ganil.fr

Organising Committee:

Jean Yves Chesnel (CIMAP), Emily Lamour (INSP),
Martino Trassinelli (INSP) and Dominique Vernhet (INSP)

Institut des NanoSciences de Paris
Campus Boucicaut
140 rue de Lourmel
75015 Paris
France

PROGRAM FOR THE SPIRAL2 MEETING

Atomic Physics Group

Thursday 27 of March	
12h	**Welcome at Boucicaut** Lunch
14h - 16h	**Round Table** *Dominique Vernhet and Jean Pierre Grandin* **Short presentations:** - context and schedule - achievements and challenges - status: technical aspects and beam characteristics SPIRAL2 compared to GANIL - what do we have to provide? Physics cases and Technical report -… **Each presentation will be followed by discussions**
16h - 16h30	**Coffe break**
16h30 - 18h	**Presentation of experimental projects (I)** Collision with ions and (bio) molecules - Dynamics *speakers:* JP Rozet, JY Chesnel, T Schlathölter, J Rangama
19h30	**Dinner at "Le Rond de Serviette"**

Friday 28 of March	
9h - 10h30	**Presentation of experimental projects (II)** Collision with clusters, surfaces and solids - Dynamics and structure *speakers:* T Zouros, JY Chesnel, O Kamalou, P Indelicato
10h30 - 11H	**Coffe break**
11h - 12h	**Conclusion** What are our needs to realize our dreamed experiments? beam intensity, charge, emittance, time structure... towards a first version for the technical requirements
12h	**Lunch at Boucicaut**

Fast Ion- Slow Ion Collisions at SPIRAL 2

C. Prigent, M. Trassinelli, E. Lamour, J.P. Rozet and D. Vernhet
(Institut des NanoSciences de Paris)

SPIRAL2 will provide not only a new range of radioactive ion beams (RIB) of high quality but also stable beans with extremely high intensities (HISB). Both opportunities open new doors for atomic physics experiments where either cross-sections, target density or detection efficiency are so small that experiments were until now hardly feasible.

Performing fast ion - slow ion collision (FISIC) experiments in the intermediate velocity regime is a long standing project for atomic collision physicists. Whereas such experiments are currently performed by high energy physicists, ion-ion collisions for atomic physics have so far been performed only in the case of slow ions, in the context of magnetically confined plasmas. Besides the fundamental interest in understanding the mechanisms involved in ion-atom collisions, such studies are also motivated by various aspects of the energy deposition of fast ions in matter, including material modifications and biological effects.

Direct and Indirect Effects in Solvated Biomolecule Radiolysis

L.Adoui, B. Gervais, B.Huber, B.Manil J.Rangama, P.Rousseau, J.Y.Chesnel
(CIMAP, Caen)

Interaction of ionising radiations with living cells containing a large amount of water is known to induce a large variety of radiation damage, like chromosomal aberration, mutations or cell death, depending on the nature of the radiation. It is customary to distinguish between direct and indirect effects to analyse the interaction of radiations with a cell. The first kind of effects arises from the interaction of the radiation with DNA itself, while the second kind arises from radiolysis of water molecules surrounding the DNA. It is however difficult to establish a clear cut between these two kinds of effects. Indeed, most of the commonly used radiations, like high-energy photons or swift light ions, generate spurs and tracks of ionisations, where a significant amount of the close-neighbour water molecules is likely to be ionised simultaneously when the radiation hits the DNA. Moreover, the extraordinary complexity of a living cell makes the elementary process at work difficult to decouple from each other.

First attempts to study how the environment may influence the fragmentation have been realised by studying the stability of clusters of biomolecules and then by checking how the neighbour molecules may influence the fragmentation observables[1]. Recently, the role of the solvent molecules has been questioned in Collision Induced Dissociation (CID) experiments in a well established collaboration with the groups of P.Hvelplund (Aarhus, Denmark) and H.Cederquist (Stockholm, Sweden). In that case (what means without electron capture or charge exchange), strong experimental evidence has been reported for a protective effect of nanodroplets of water attached to the RNA nucleotide adenosine 5'–monophosphate (AMP) molecule. It was for example found that 20 (or more) water molecules completely protect the AMP from being damaged. This has been explained by means of a common simple water evaporation model[2]. The situation can be very different in the case of capture or ionisation mechanisms. Internal energies of the biomolecule-water complexes can be modified and the excitation energy distribution before fragmentation different. Some preliminary experiments have been conducted in order to study ECID (Electron Capture Induced Dissociation) on the Aarhus platform (Denmark) in strong collaboration with the Caen group[3].

The purpose of this project is to understand, *at the molecular scale*, the interaction of ionising radiations with model bio-molecular systems made of small DNA or RNA building blocks solvated in a controlled amount of water molecules. Model systems, identified by an interdisciplinary collaboration joining physicists, chemists and biochemists, will be studied on multi time-scales depending on the molecule environment. We ambition to establish a clear, complete and quantitative evaluation of the direct and indirect effects induced by ionising radiations interaction with molecules solvated in aqueous solutions. We propose to combine experimental and theoretical approach for the achievement of our project. Experiments with finite systems, either isolated or partially solvated molecules, are aimed to provide essential data regarding the dissociation pathways, which are difficult to predict accurately, and to impose tight constraints for the development of a powerful simulation. In turn, the simulation based on *ab initio* and reactive classical molecular dynamics allows interpretation of the experiments in term of solvation. It is the only way to provide the necessary input for extrapolation towards complete solvation in liquid by means of Kinetic Monte Carlo simulation.

We will discuss at the meeting the interest to perform such experiments in the case of swift charged ion projectile – in the maximum Linear Energy Transfer range – as well as the ion beam characteristics required for such developments.

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[2] B.Liu, S.Brøndsted Nielsen, P.Hvelplund, H.Zettergren, H.Cederquist, B.Manil and B. A.Huber, Phys. Rev. Lett. 97, 133401 (2006)
[3] B.Liu, N.Haag, H.Johansson, S.Brondsted Nielsen, H.Zettergren, P.Hvelplund, B.Manil, B.A.Huber J.Chem.Phys. 128 075102 (2008)

Heavy ion induced radiation damage studies in DNA/protein complexes

Thomas Schlathölter *et al* (KVI, Groningen)

With the advent of the electrospray ionization technique, it is now possible to bring virtually any protonated or deprotonated biological macromolecule into the gas phase. This opens up the opportunity to study for instance biological radiation damage on the molecular level using realistic models of a cell nucleus (which should consist of DNA *and* proteins). To study the response of such macromodels upon heavy ion irradiation, it is suggested to employ a crossed-beam technique and analyze the reaction products using the COLTRIMS technique. The major current obstacle for such studies is the low output of an electrospray ion source, which amounts to not more than several pA for size selected beams of biomolecular ions. It is thus necessary to employ very high fluence heavy ion beams (as potentially available from the SPIRAL 2 facility) to reach event-rates suitable for experimental studies.

Fragmentation of size-selected clusters after irradiation by intense HCI beams

Jimmy Rangama *et al*., (CIMAP, Caen)

HCI beam is a good tool to induce strong perturbations in atomic and molecular finite systems. We plan to perform collisions, in crossed and merged beam configurations, between metal and semiconductor size-selected clusters and ultra intense HCI beams available at SPIRAL 2 installation. We are already able to produce and transport size-selected cluster (from n=2 to 10000) beams of metallic and semi conducting materials with a well defined geometry and kinetic energy. Cluster beams can be pulsed to do time-of-flight spectrum measurements or continuous in order to measure energy-over-charge spectra. In such experiments, it is well known that the number of events depends critically on the projectile (HCI) and target (clusters) beam densities. SPIRAL 2 should be able to provide ultra intense HCI beams for crossed and merged beam experiments. The relative energy of the collision should influence the ionisation cross section. It will be possible to study the effects of size on the fragmentation patterns as well as charge mobility effects on the cluster stability.

Zero-degree Auger projectile spectroscopy at SPIRAL2 ?

Theo Zouros (University of Crete-Heraklion, Crete, GREECE)

The expected high quality SPIRAL2 beams (low emittance of μA to mA currents) of light to intermediate Z, highly charged ions (HCI) with A/q ≤3 (possibly even ≤6) and energy spread of ΔE/E ≤ 0.6% in the collision energy range of 0.75 – 14 MeV/u will provide new challenges and prospects for accelerator based atomic collisions. In particular, techniques investigating the collisional excitation of the projectile ions or weak processes limited primarily by low beam currents can be expected to gain.

The technique of *zero-degree Auger projectile spectroscopy* (ZAPS) [1] in which Auger electrons emitted from an HCI of a particular charge state q is measured with enough energy resolution (typically $\Delta E_e/E_e \leq 0.1\%$) to provide state selective cross section information on the excitation process is clearly among those which stand to benefit. However, the unusually high intensity beams can also be expected to provide new design challenges since the use of slits to collimate the ion beam and define the electron energy resolution of the in-beam spectrometer as well as the small apertures used on the target gas-cell in the conventional ZAPS approach will be problematic if not impossible to implement. New design features possibly using dense cluster gas jet targets, first-stage magnetic deflection or virtual entry slits [2] and possibly even a high density crossed electron beam target might be considered to overcome some of these difficulties.

Binary encounter electron production of 1 MeV/u intermediate –Z HCI could be investigated for two-center and ionization saturation effects. Additionally, more rare highly-correlated three-electron resonant processes could also be looked for, such as R1T2E (Resonant Transfer of 1 electron with the simultaneous excitation of 2 projectile electrons) [3] or R2T1E (Resonant Transfer of 2 electrons with the simultaneous excitation of 1 projectile electron) [4]. Both these processes remain of interest, but have been searched for in the past with rather dubious if any success. Furthermore, the production of hollow 3- [5] and 4-electron states [6] created in direct triple or quadruple capture to high intensity bare ion beams are also of present interest [7] due to the highly correlated nature of their states with no other good way to readily produce them for study.

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[2] E. P. Benis *et al*, Physica Scripta T**80B**, 529-31 (1999) and references therein.
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[6] T.J.M. Zouros *et al*., Nucl. Instr. Meth. Phys. Res. B**233**, 161-171 (2005).
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Search for rare three-electron-Auger processes

H. Rothard, B. Manil, A. Cassimi, Ph. Boduch (CIMAP Caen)
S. Hagmann (IKF Goethe Univ. Frankfurt and GSI Darmstadt)
G. Lanzanò, E. De Filippo (INFN Sect. de Catania)

We suggest using the high intensity beams of Spiral 2 (including an improved duty cycle as compared to the actual SME beams) to search for a rare Auger process involving three electrons. If for example the atomic K-shell is empty, and three electrons are located in the L-shell, two of the three L-shell electrons "simultaneously" transit to the K-shell and transmit the gained energy to the *one* single electron left in the L-shell ($K^2L^2L^1$ transition). One way to prepare such "hollow atoms" is via target electron capture to outer shells of slow highly charged ions approaching a surface [1,2]. Another possibility is the formation of inner shell vacancies with non-negligible probability of producing two inner shell vacancies (in the % range) in ion-atom collisions with nearly symmetric collision systems [3]. A proposal to search for such processes in beam-foil excited Carbon ions was recently accepted at LNS/Catania [4]. Target Auger electrons from e.g. carbon can be measured with electrostatic electron spectrometers [5]. It is conceivable to find three electron Auger processes, because ions above approx. Z=15 (e.g. Ar) at SME/Spiral 2 energies produce a large amount of doubly ionized K shell atoms (approx. 20 %). The ionized L shell of Carbon is re-filled in less than a fs and thus the above condition of at least 3 electrons present in the L shell is fulfilled at the time of K-Auger decay (8-15 fs). Such experiments were already performed at Ganil-SME, but the statistics were to low to identify such rare processes (approx. 10^{-4} compared to two-eletron "ordinary" Auger processe). One may also speculate about the possibilities of a beam-foil experiment with C beams to search for projectile three Auger electrons. Furthermore, one can speculate about the possibility to perform an (ion in, two electrons out) experiment on correlated electron emission (which may give information about charge screening in insulators versus conductors).

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HCI Cooling and Mass Measurements with RIB using Penning Traps

O. Kamalou, M. Hobein, A. Solders, M. Suhonen, L. Hyuwen, Sz. Nagy[1], K. Blaum[1], and R. Schuch

(Atomic Physics, FYSIKUM, Stockholm University, Stockholm)

([1]Physics Department, Johannes Gutenberg University, Mainz)

The mass of an atom and its inherent connection with the atomic and nuclear binding energy is a fundamental property of the atomic nucleus. Accurate mass values are therefore of importance for variety of application in nuclear and atomic physics studies ranging from the verification of nuclear models and test of the standard Model to determination of fundamental constants. In nuclear structure studies the nuclear binding as the missing mass of the bound system m(N,Z) compared the sum of all masses of the constituent protons Z m_p and the neutrons N m_n :

$$B(N,Z)= N m_n + Z m_p - m(N,Z)c^2$$

The long observation time and the well understood dynamics of the ions motion in penning trap makes it possible that the Penning trap mass spectrometers compete in the front lines of high precision mass spectroscopy. This technique has the potential to provide high accuracy and sensitivity in nuclear ground state properties e.g. in the nuclear charge radii and in the quadrupole moment by laser spectroscopy even for very short-lived radionulides. Furthermore, ion traps can be used and offer an advantage for precision decay studies.

Hyperfine quenching for highly-charged stable and radioactive ions at SPIRAL II

Paul Indelicato (Laboratoire Kastler Brossel, Paris)

Our group has proposed to do experiments at SPIRAL II for measuring hyperfine quenching (reduction of the lifetime of long-lived atomic levels due to the interaction with the atomic nucleus magnetic moment). These measurements are typical “beam-foil” measurements. There are two different kinds of experiments of that kind that can be done. One is to use very intense, stable beams of few-electron ions with the LINAG. One can use the high intensity to prepare a high quality beam (very parallel, well aligned) and obtain very precise measurements. Such measurements would be done as accurate tests of relativistic atomic theory in few electron systems. A second possibility would be to use radioactive beams, after the CIME cyclotron. One would then have to identify beams intense enough to allow such measurements, and develop a specific set-up to use them efficiently. The aim would be to deduce the value of the nuclear magnetic moment of unstable nuclei. Depending of the atomic number, helium-like, beryllium like or magnesium-like ions could be used. One would have first to calibrate the ion species on stable beams of known magnetic moment (at present only helium-like ions have been extensively studied). A second line of experiment that we could propose at SPIRAL II, would be to use low-energy radioactive beams, and do mass spectroscopy using an electrostatic trap that has been adapted for use with highly charged ions, from a model developed by D. Zajfman of the Weismann Institute.

GANIL and SPIRAL2 projects

A.Cassimi, H.Rothard, B.Ban-d'Etat, P.Boduch, H.Lebius
(CIMAP,Caen)

Several research topics in atomic and molecular physics as well as in solid state physics are performed at GANIL. These experiments take great advantage of the time structure of the ion beams available at this facility. More precisely, GANIL is the only place around the world where a one nanosecond ion pulse every few µseconds is available. This is a decisive advantage for the following fields of research.

Atomic and molecular physics:

At GANIL, a so-called COLTRIMS apparatus is available since nearly 15 years. It is based on correlated time-of-flight and position measurements, which allows to determine precisely the momenta of all collision products. Kinematically complete experiments are performed with this spectrometer[1-3]. The typical atto-second duration of ion-molecule collisions leads to the full determination of ion-induced free molecular fragmentation (CO, CO_2, H_2O, N_2) and to molecular ion spectroscopy. This technique will be extended to ion-cluster (Ar_n, $(H_2O)_n$), interaction studies as well as to ion-induced chemistry in (bio-)molecule-seeded clusters (such as $(H_2O)_n$). One of the major interests of GANIL beams is that the ion energy range covers the maximum stopping power region.

Surface and solid state physics:

The combination of imaging techniques (XY) and time-of-flight (TOF) spectroscopy can also be applied to the case of particle ejection in swift ion collisions with solids. A straightforward application consists in detecting secondary electrons [4] and secondary ions [5]; in a second step, post-ionization techniques may be used to detect ejected neutrals.

Such ejected particles are an important experimental signal, so to say a "messenger" for the dynamics of energy deposition and relaxation by swift ions in condensed matter. Particularly interesting information is the energy spectrum of emitted electrons or secondary ions, but here a crucial point is an optimized time resolution (projectile pulse width) combined with the possibility to have projectile pulses separated by a time somewhat larger than the maximum time of flight of the ions to be detected. This can be achieved with a pulse suppressor as available at GANIL.

GANIL vs SPIRAL2:

The key point for reaching a good resolution is the pulse duration. Since this technique is based on time of flight measurements, two parameters are crucial:

the pulse duration determines the final resolution of the measurement: 1ns or less is needed.

the repetition rate has to be low in order to avoid random coincidences: 1 to 5 µs repetition period is better fitted to this kind of experiment.

Combined with the pulse suppressor, GANIL is the best facility in the world for such experiments and it is therefore highly advisable to continue to make available to the community this "high-tech" tool in state of the art time-of-flight/imaging experiments.

Hopefully, SPIRAL2 could improve these characteristics so that we can become SIPRAL2 users.

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Interest in performing atomic and molecular physics experiments at SPIRAL2

Béla Sulik and Zoltán Juhász (ATOMKI Debrecen, Hungary)

We consider SPIRAL2 as a source of very intense beams of HCI-s in a wide energy range from a few 100 keV/u up to a few 10 MeV/u. With intense beams, crossed-beam experiments may be planned. Related ideas are as follows.

For ion - (bio) molecule collisions, intense beams might open a possibility for "generation" experiments of consecutive collisions. The idea is the following: a (bio)molecular gas jet interacts with a very intense ion beam. Then the fragments are extracted and formed into secondary beam(s). This latter beam(s) may collide with a third - again, very intense - beam (might be again the first kind of beam) to model secondary collisions in more dense tissues. Collision cascades are probably important in radiation damages. The chance of doing such experiments successfully depends not only on the vacuum levels and on the studied processes themselves; it also depends on the beam intensities. This is the reason why we would like to take advantage of the SPIRAL2 facility to perform these experiments. It is also important here that pulsed beams can help in using e.g., large solid angle TOF spectrometry. Since individual collision cascades may have very low probabilities, TOF methods can be used even with intense beams. In special cases, even coincidence between low probability channels might be studied with intense beams. For such experiments, beam intensities are hard to estimate in general. It depends on the collision problem. Also, charge states may vary from low to high charge states.

Fragmentation is an important topic in the field of radiation damage in general. Since the ion-energy range available at SPIRAL2 is expected to be rather wide, systematic studies for mapping the different parts of the Bragg peak might also be possible, which can be useful to develop our microscopic understanding in the stopping process (or linear energy transfer, LET). For such collisions, the charge states should be selected according to the studied collision energies, since the mean charge state of the decelerating ions strongly varies with energy.