Title of the Project : Quantum dynamics in ion-ion / ion-atom collisions

Supervisor(s), Laboratory: Emily Lamour, Christophe Prigent - INSP

1. Context and Research Problem

Study of primary electronic processes in collisions between ions and matter is of great importance in many research domains and specially to understand the time dynamics of plasmas. Such fundamental interactions occur notably in interstellar media, at the edges of tokamak plasmas and in inertial fusion plasmas. In fact, when multicharged ions interact with matter, the latter is subjected to strong fields (which can reach up to 10^{11} V/m), often for extremely short durations (from femtoseconds to a few attoseconds) inducing complex electronic dynamics. For instance, in ion-matter collisions, the incoming ion may capture electrons (charge exchange) from the other partner, loses part of its own electrons (ionization) or the latter may be promoted in excited states (excitation). The probability (or cross-section) of electronic processes depends on the relative velocity between the two collision partners but also on the number of electrons initially bound to each nucleus. While the collision dynamics are fairly well understood at low (molecular regime) and high (perturbative regime) velocities, the intermediate regime is characterized by the fact that, there, all the primary electronic processes reach their optimum probability with amplitudes of the same order of magnitude. This makes difficult measurements of a well-defined process while this collision regime correspond to the one for which the ion energy deposition in (hot or cold) matter reaches its maximum. By performing systematic studies as a function of the number of initial electrons through ion-bare ion to ion-atom collisions, original data on the quantum dynamics of N-body systems will be obtained in this hitherto unexplored regime.

2. Scientific Objective

For several years, the ASUR team at INSP has been developing a cross-beam experiment to carry out ion-atom (well known since decades for a large of atomic systems and used here as benchmarks) and ion-ion collisions (studied up to now in the low-energy regime for a few systems). The goal is to investigate collisions from the pure 3-body problem (a bare heavy ion colliding with a hydrogenic target as a benchmark) to the study of the role of electrons added more or less one by one. Based on X-ray and ion spectroscopy techniques, the goal is not only to measure absolute cross sections (mandatory as inputs for plasma codes) but also to have access to the dynamics thanks to coincidence measurements between the X-rays emitted during the collision and the final charge state of the ions after the collision. Investigations will be carry out from the low-velocity collision regime to the intermediate one. This strategy is to start from a regime where the cross sections are relatively well known, so as to test the experimental tools, to study a regime for which there is a real lack of both experimental and theoretical data, i.e. a real “terra incognita” for atomic physics. Systematic studies for a large variety of collision systems are expected to be conducted to provide an extensive database to improve and extend theories and simulations related to ion-matter interactions, whether the matter is cold, or in plasma form (interest for the astrophysics and plasma communities).

3. Justification of the Scientific Approach

At INSP, two platforms, named FISIC and SIMPA, are now installed for the investigation of ion–ion/atom collisions. Each platform is equipped with an electron cyclotron ion source and its beam line capable of delivering keV/uma ion beams well characterized in terms of current, flux and shape. On one hand, with these INSP facilities, depending on the system (up to atomic number 18 corresponding to argon), studies from the low-velocity regime to the intermediate one can be carried out. On the other hand, the FISIC platform connected to the CRYRING storage ring at GSI/FAIR in Germany[1] will give the possibility to explore from the high velocity regime down to the intermediate one with heavier systems (atomic numbers > 18).

While the collision chamber for ion-ion collisions is ready, the one for ion-atom has to be designed to permit the installation of an effusive gas jet. Two detection systems will be used: a Silicon Drift Detector to record the X-ray emission and an ion spectrometer (developed in **collaboration with the CIMAP laboratory at GANIL**). The X-ray detector has been recently fully characterized in terms of resolution and efficiency. An ion spectrometer has been manufactured and characterized in terms of charge state separation and resolution (previous fellowship of IPI). The last step will be to adapt a detection system to measure at the same time the number of ions with an unchanged charge -currents of µA) state together with the charge–changed ions (currents of pA-nA). Finally, our experimental approach is to perform coincidence measurements thanks to our new acquisition system fully equipped.

[1] This part of the project is included in a French-German collaboration.

While the doctoral project is mainly an experimental project, the obtained data will be discussed and compared to the most sophisticated theoretical approaches under development whether these approaches are perturbative (valid for high energy collisions) or non-perturbative (valid for low-velocity collisions) thanks to our close **collaborations with N. Esponda[2] et al from Instituto de Física Rosario** (Atomic Collisions Group - Argentina) and **A. Dubois[3] from the LCPMR** (Sorbonne University) and member of the Plas@par Federation.

4. Work Plan

Work Packages (WP) *Milestones (M)*	1st Year				2nd Year				3rd Year			
WP1: Ion-Atom Collisions												
M1.1: Chamber: design and installation	■	■										
M1.2: X-ray spectroscopy.			■	■			■	■				
M1.3: Ion spectroscopy					■	■	■	■				
M1.4: Coincidence measurements							■	■				
WP2: Ion Spectrometer												
M2.1: Simulation of ion trajectories	■	■										
M2.2: Dectection design		■	■									
M2.3: Manufacture and tests				■	■							
WP3: Ion-Ion collision												
M3.1: Experiment @INSP							■	■				
M3.2: Installation of FISIC @CRYRING									■	■		
M3.3: First measurements @CRYRING											■	■

5. Alignment with the PLAS@PAR Program

The present project enters in the study of microscopic processes in plasmas (ionisation, collisions and interaction processes). With this doctoral project, we intend to measure cross sections in a collision regime never explored up to now, i.e. the regime linked to the maximum ion energy transfer in matter. Those cross sections will be used as inputs to uderstand the temporal dynamics of plasmas.

6. Supervision and Expertise

E Lamour is used to performed experiments on large scale facilities such as GANIL and GSI and is responsible for the SIMPA platform at INSP where the FISIC platform is also now installed. She is the scientific coordinator of the international FISIC collaboration that includes experimentalists and theoreticians. Christophe Prigent is an expert in ion source and ion beam productions. He has a long and well-recognized experience in X-ray spectroscopy. E lamour and C Prigent are in close contact with the atomic physics group of CRYRING/FAIR/GSI installation.

7. Publications and Collaborations

Collaborations : National collaborations : LCPMR (Sorbonne University), CIMAP laboratory at GANIL/Caen.
International collaborations : Atomic Physics group og GSI/FAR, Giessen University, Instituto de Física Rosario (Atomic Collisions Group - Argentina).

Papers of the team related to the project :

- F. Aumayr et al, Chapter 3 - Collisions involving heavy projectiles, E. Lamour, Ion–ion collisions in the intermediate velocity regime; J. Phys. B: At. Mol. Opt. Phys. 52 (2019) 171003

[2] Thanks to obtaining a Franco-Argentine scholarship, N. Esponda was able to spend 4 months with the team (September-December 2024) to start calculations based on a perturbative approach.
[3] A. Dubois was the co-director of the Mariette Jolly PhD thesis with an experimental part supervised by E. Lamour and a theoretical part based on non-perturbative calculations develpped by the LCPMR team.

- D. Schury, A. Méry, J. M. Ramillon, L. Adoui, J. Y. Chesnel, A. Lévy, S. Macé, C. Prigent, J. Rangama, P. Rousseau, S. Steydli, M. Trassinelli, D. Vernhet, A. Gumberidze, Th. Stöhlker, A. Bräuning-Demian, C. Hahn, U. Spillmann and E. Lamour, the low energy beamline of the FISIC experiment: current status of construction and performance, J. Phys.: Conf. Ser.1412 (2020) 162011
- D. Schury, A. Kumar, A. Mery, J.-Y. Chesnel, A. Levy, S. Mace, C. Prigent, J.-M. Ramillon, J. Rangama, P. Rousseau, S. Steydli, M. Trassinelli, D. Vernhet, and E. Lamour, An electrostatic in-line charge-state purification system for multicharged ions in the kiloelectronvolt energy range, Review of Scientific Instrument 90 (2019) 083306
- M. Jolly, S. Voikopoulos, E. Lamour, A. Méry, A. Bräuning-Demian, J.-Y. Chesnel, A. Gumberidze, M. Lestinsky, S. Macé, C. Prigent, J.-M. Ramillon, J. Rangama, P. Rousseau, D. Schury, U. Spillmann, S. Steydli, T. Stöhlker, M. Trassinelli and D. Vernhet, Atoms 10 (2022) 146
- M. Jolly, E. Lamour, C. Prigent, S. Macé, M. Trassinelli, P. Velten, O. Cosson, X. Donzel, P. Cailliau, L. Maunoury, Production of C6+ ions with a Supernanogan ion source at moderate RF powers, submitted to NIMA