the main scientific goals and motivations

a status report of the project on SPIRAL2
The FISIC PROJECT

The main goals

Fundamental studies of quantum dynamics of N-body systems in atomic collisions when ion stopping power is maximum (relevant for the AMO Physics)

determination of absolute cross sections of elementary collision processes with an ultimate control on dressed orbitals of the projectile AND the target ions

From a pure 3-body system

ionization, excitation, capture
The main goals

Fundamental studies of quantum dynamics of N-body systems in atomic collisions when ion stopping power is maximum (relevant for the AMO Physics)

determination of absolute cross sections of elementary collision processes with an ultimate control on dressed orbitals of the projectile AND the target ions

From a pure 3-body system

ionization, excitation, capture

exploration of the collision regimes:

\[ K = \frac{v_e}{v_p} \times \frac{Z_t}{Z_p} \]

(for projectile electrons)

K >> 1 \quad \text{non-perturbative regime}

K \sim 1 \quad \text{intermediate regime}

K << 1 \quad \text{perturbative regime}
The main goals

Fundamental studies of quantum dynamics of N-Body systems in atomic collisions when ion stopping power is maximum (relevant for the AMO Physics)

determination of absolute cross sections of elementary collision processes with an ultimate control on dressed orbitals of the projectile AND the target ions for N-body systems

— ionization, excitation, capture —

same order of magnitude
high contribution of multiple processes

almost impossible

► to quantify the role of each electron
► to disentangle single and multiple processes
► to quantify the multiple processes

THE FISIC PROJECT
The main goals

Controlling the projectile and target orbital occupation……

in Fast Ion - Slow Ion Collisions

for a wide range of collision systems, i.e. \( Z_p \) & \( Z_t \)

- to benchmark the theoretical approaches
- to explore the role of additional electrons – one by one –
  - tuning closure of different channels
  - effects of electron – electron interactions
  - multiple processes… often neglected!
  - role of Coulomb forces
THE FISIC PROJECT

Cross sections of electronic processes in ion-ion collisions

- barely known when ion stopping power is maximum

- in plasmas
  - stellar and interstellar
Fast Ion - Slow Ion Collisions

barely known when ion stopping power is maximum

- in plasmas
  - stellar and interstellar
  - inertial confinement fusion

THE FISIC PROJECT

motivations
**THE FISIC PROJECT**

**Fast Ion - Slow Ion Collisions**

barely known when ion stopping power is maximum

- in plasmas
  - stellar and interstellar
  - inertial confinement fusion

- in ion-matter interaction

![Graph showing relative dose vs penetration depth in tissue](image-url)
Recent progress

Fast Ion - Slow Ion Collisions

Experimentally: ions through plasmas...

- WDM plasma effects probed via the measurement of the charge state distribution of a laser generated C ion beam (0.045-0.5 MeV/A)

Coll. LULI@ELFIE & INSP


with perspectives towards XFEL for ultrafast isochoric heating up to 100 eV
**THE FISIC PROJECT**

**Fast Ion - Slow Ion Collisions**

Experimentally: **ions through plasmas...**

- Ion energy loss measurement in a laser-generated carbon plasma ($N_e=10^{21} \text{ cm}^{-3}$, $T_{e\text{max}} \sim 180 \text{ eV}$) at maximum stopping power

Energy deposition significantly smaller (~135%) than predicted by perturbative approaches.

**Coll. CELIA, CEA/CESTA & TU-Darmstadt/GSI**

W. CAYZAC PhD Univ. Bordeaux & TU Darmstadt, 2013 see also Franck *et al* PRL110 (2013)

challenging experiments & limited to specific systems
Theoretically:

Extension of the validity domain of non-perturbative methods

Coll. INSP & LCPMR

“Emergence”
Recent progress

Theoretically:

Extension of the validity domain of non-perturbative methods

Coll. INSP & LCPMR

G. Labaight, PhD UPMC, Sept. 2014

H\(^+\) on Li (3 e- system)

@ 4 keV/u

K >> 1

@ 80 keV/u

K < 1

THE FISIC PROJECT

a complete experimental program
THE FISIC PROJECT: WHAT IS NEEDED?

- **a crossed-beam device**
- **Targets:** low energy ion beams (keV/u) with control of the ionization state
  - need to purify the beam prior to the collision zone
  - ⇒ Low density targets
- **Projectiles:** high energy ion beams (MeV/u) with high intensities
  - $10^{12}$-$10^{13}$ sec$^{-1}$, good optical quality and perfect selection of the ion charge state
- **Coincidence measurements:** projectile/target charge changes, $X/$ ion
- **Efficient detection systems**

For instance: $\text{Ar}^{q+} + \text{Ar}^{q+} @ 8\text{MeV/u}$
**THE FISIC PROJECT**

*Charge exchange cross section measurements for the day-one experiment*

**HE ion beam Q+ (MeV/u)**
with high intensities

**LE ion detection**

**LE ion beam q+**
*(source @ U₀)*

**HE ion detection**
*also at CRYRING/FAIR*

**Capture on HE channel:**
\[ \text{Ar}^{18+} + \text{Ar}^q \rightarrow \text{Ar}^{17+} + \text{Ar}^{(q+1)+} \]

**Ionization on LE channel:**
\[ \text{Ar}^{18+} + \text{Ar}^q \rightarrow \text{Ar}^{18+} + \text{Ar}^{(q+1)+} + e^- \]

**Position sensitive Faraday Cup Array**

**Electrostatic selectors**

**UHV collision chamber**
10⁻¹¹ mbar

**Electrostatic analyzer**

**Coincidences**
**A National & EU priority**

**SPIRAL2**

### Phase 1 (2015)
Increase the intensity of stable beams by a factor 10 to 100 – High intense neutron source

$10 \mu A \ (6 \times 10^{13} \text{pps}) A < 50$

### Phase 1++ (2019)
(A/Q=6-7 Injector)

$10 \mu A \ (6 \times 10^{13} \text{pps}) A > 50$

- Linac driver
  - 33 MeV $p$, 40 MeV $d$ (5 mA)
  - A/q=3 - 14.5 A MeV HI (1 mA)

### Phase 2 (>2020)
- Produce exotic nuclei in abundance (factor 10 to 1000 higher than present facility)
- Expand the range of exotic nuclei to $A > 80$
- Post-acceleration of high intensity RIB

### DESIR Phase 1+ (2018)
(low energy facility)

### AGATA (2015-2018)

**SPIRAL1 Upgrade (2016)**
New light RIBs from beam/target fragmentation

**SPIRAL2 is on the list of the European Strategy Forum on Research Infrastructures (ESFRI)**
THE S3 ROOM FOR NUCLEAR AND ATOMIC PHYSICS

**Target room for nuclear reactions and/or stripping**

**Beam**

**Selection & Identification**
- Time of flight + Energy
- A measurement

**Ground state measurement (gas catcher)**
- $\beta/\beta$–delayed
- Laser spectroscopy
- Mass measurement
- Chemistry

**PHASE 1**

**Two step reactions**
- Transfer+Fusion (transfer)

**Specific Modes**
- Ion-ion collision: FISIC Program

**PHASE 2**

**Beam dump for 99% of the beam**

**Multi-purpose Experimental Room**

**Delayed spectroscopy**
- p, α, γ, e- decay

**DESIR**
THE FISIC PROJECT @S3/SPIRAL2

High Energy Ion Beam with charge $Q^+$

Stripper

INSP/GANIL/GSI

Desorption yield measurements@ GSI, summer 2014

INSP/Irfu/GSI

Low Energy Ion Beam with charge $q^+$

Collider & detection systems

Multi-coincidences

High Energy detection

INSP/Irfu

Beam Dump FISIC (5kW max)
THE FISIC PROJECT @S3/SPIRAL2

Collider under $10^{-11}$ mbar

chamber & detection systems

$10^{-9}$ mbar
THE FISIC PROJECT @S3/SPIRAL2

breakthrough in atomic collision physics

S3: Super Separator Spectrometer

Fast Ions from SPIRAL2
from C to Ni ions
(0.75 \leq E \leq 14.5 \text{ MeV/u})

Slow Ions from an ECR source
with from C to Ar of 3 \leq q \leq Z
@ E \leq 20 q \text{ kV}

ANR-13-IS04-0007- Fit-FISIC
Kick-off meeting: March 2014

ANR
DFG Deutsche
Forschungsgemeinschaft

FIT-FISIC
S^3

EQUIPE S^3

Inspriation
CiMap
Helmholtz Gemeinschaft
GSI
the FISIC project
An update of the collaboration

Status

Meeting with theorists, Sept. 2014

O Fojon, JM Monti, R Rivarola, C Stia, C Tachino- IFIR, Rosario, Argentina
S Otranto - Bahía Blanca, Argentina & Missouri University USA
R Barrachina, F Colavecchia, D Fregenal- CNEA, Bariloche, Argentina
C Champion - CENBG, Bordeaux France
S Fritzsche, GSI, Darmstadt, Germany
C Lemell – ITP- TU Wien, Austria
Within the Plas@par Labex: **new generation of X-ray spectrometer**

**Coll. INSP, LCPMR**

- 1% of global efficiency
- Resolution 1 eV @ 3000 eV (100µm of spatial resolution)

**Possibility of X/ion coincidence measurements towards excitation processes**
FISIC project in the S3 room...

Stripping @ high intensity; Coll. INSP, GANIL, GSI

Collision systems available with injector A/q=3

<table>
<thead>
<tr>
<th>targets, 1+ to fully stripped</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
</tr>
<tr>
<td>C^{6+},5+,4+</td>
</tr>
<tr>
<td>O^{8+},7+,6+</td>
</tr>
<tr>
<td>Ne^{10+},9+,8+</td>
</tr>
<tr>
<td>Ar^{18+},17+,16+,15+,14+</td>
</tr>
<tr>
<td>Ni^{28+}, 27+,........18+</td>
</tr>
</tbody>
</table>

ETACHA Code

Ni^{18+} 14 MeV/u on C

2D simulations

**Recent progress**

**Fast Ion - Slow Ion Collisions**

Experimentally: ions through plasmas...

- Ion energy loss at maximum stopping power in a laser-generated plasma in carbon foil $(N_e = 10^{21} \text{ cm}^{-3}, T_{e\text{max}} \sim 180 \text{ eV})$

**Coll. CELIA, CEA/CESTA & TU-Darmstadt/GSI**

Franck et al/ PRL110 (2013)
FISIC project in the S3 room... count rates and vacuum conditions

\[ \text{Ar}^{Q+} (8\text{MeV/u}, I_1=50\mu\text{A}) + \text{Ar}^q+ (U=U_0-\Delta V) \rightarrow \text{Ar}^{(Q-1)+} + \text{Ar}^{(q+1)+} \]

R(counts / s) = \frac{1}{D} \frac{\sigma I_1 I_2}{Q_1 Q_2 v_2 \bar{z}}

with D = 1 and z = 2mm

<table>
<thead>
<tr>
<th>HE ion</th>
<th>( \sigma_{\text{capt}} ) (cm²)</th>
<th>LE ion</th>
<th>( I_2 ) (μAe)</th>
<th>( \sigma_{\text{ion}} ) (cm²)</th>
<th>U (kV)</th>
<th>( R_{\text{capt}} )/s</th>
<th>( R_{\text{ion}} )/s</th>
<th>Background HE /s</th>
<th>Background LE /s</th>
<th>( \Delta t ) (ns)</th>
<th>fortuitous coincidences</th>
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<tr>
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<td>25=20+5</td>
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<td>&lt;2</td>
<td>24</td>
<td>7</td>
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<td>30</td>
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<td>Ar^{18+}</td>
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P=10^{-9} mbar over 7.5m

P=10^{-11} mbar over 0.5m

with 2ns of resolution
### FISIC project in the S3 room... count rates and vacuum conditions

\[ \text{Ar}^{Q+} (8 \text{MeV/u}, I_1=50 \mu\text{A}) + \text{Ar}^{q+} (U=U_0-\Delta V) \rightarrow \text{Ar}^{(Q-1)+} + \text{Ar}^{(q+1)+} \]

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<td>326 !!!</td>
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Among 5 physics cases, only one remains feasible with \( 5 \times 10^{-8} \text{ mbar} \) vacuum in S3 => a crucial point

\[ P=5 \times 10^{-8} \text{ mbar over 7.5m} \]

\[ P=10^{-11} \text{ mbar over 0.5m} \]

with 2ns of resolution
FISIC project in the S3 room...

- HE ion detection system

Depending on E, Q and M:
- Segmented diamond detectors
- Secondary electron detectors based on MCPs with position sensitive anodes

Collaboration with Atomic Physics group GSI and Jena Univ

Tests of HE ion detectors at CRYRING in 2015
Further perspectives for Atomic Physics in the intermediate velocity regime

- Collision dynamics between SPIRAL2 ion beams and very low density targets ions, electrons, mass selected clusters and bio-molecules.

FISIC

mechanisms such as resonant transfer excitation

Fragmentation (Size, temperature, charge mobility effects)

Crossed beam experiments; (multi-)coincidence measurements
Studies in the intermediate collision regime

✓ Ion-atom collisions: \( \text{Ar}^{16+} @ 13.6 \text{ MeV/u on neutral } Z_t \)

Possibility to isolate the single excitation process \((1s \rightarrow 2p)\) from multiple processes

Perturbative calculation
Scaling law with \(Z_t^2\)

Compare to exp. data
strong decrease of \(\sigma_{\text{exc}}\)
more than one order of magnitude

Role of target electrons through e-e interactions
\(\Rightarrow\) screening and antiscreening effects
Studies in the intermediate collision regime

✓ **Ion-atom collisions: Ar^{16+} @ 13.6\text{MeV/u} on neutral Z_t**

Possibility to isolate the single excitation process \((1s \rightarrow 2p)\) from multiple processes

Screening and antiscreening effects / role of target electrons in ionization / excitation

- **Screening**: is almost complete
- **Antiscreening**: is very small but target e⁻ contribute to excitation or ionization
Studies in the intermediate collision regime

✓ Ion-atom collisions: Ar\(^{16+}\) @ 13.6 MeV/u on neutral \(Z_t\)

Possibility to isolate the single excitation process (1s→2p) from multiple processes

Perturbative calculation
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Role of target electrons through e-e interactions
⇒ screening and antiscreening effects

Symetric Eikonal calculations
Not tested for other conditions!
Studies in the intermediate collision regime

✓ Ion-atom collisions: Ar$^{16+}$ @ 13.6MeV/u on neutral $Z_t$

Possibility to isolate the single excitation process ($1s \rightarrow 2p$) from multiple processes
**Studies in the intermediate collision regime**

✓ **Ion-atom collisions: Ar\(^{16+}\) @ 13.6MeV/u on neutral \(Z_t\)**

Possibility to isolate the single excitation process (1s→2p) from multiple processes

For example:
- CI negligible for low \(Z_t\)
- CI 54% of SE for Xe

Beyond a pure 3-body case, none of the most sophisticated theories is able to treat all the processes on the same footing!