Preparations for the FISIC experiment at SPIRAL2

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GSI Darmstadt

- the main scientific goals and motivations
- a project status report

**FISIC**: Fast Ion- Slow Ion Collision ; a collider on S3/SPIRAL2/GANIL
for Atomic Physics
Research program of the FISIC project

The main goals

Fundamental studies of quantum dynamics of N-body systems in atomic collisions when ion stopping power is maximum

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
Research program of 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

exploration of the collision regimes:

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

\[
\begin{align*}
&K >> 1 & K \sim 1 & K << 1 \\
&\text{non-pertubative} & \text{to} & \text{pertubative regime}
\end{align*}
\]
Research program of 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

exploration of the collision regimes:

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

\( K \sim 1 \)

intermediate regime
Research program of 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

for N-body systems

ionization, excitation, capture

K ~ 1

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
Research program of 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. Zp & Zt

- to benchmark the theoretical approaches
- to explore the role of additional electrons – one by one –
  - tuning closure of different channels
  - effect of electron – electron interactions
  - multiple processes... often neglected!
  - role of Coulomb forces

From 3- to N-body systems
Study of atomic collisions in which regime?

Cross sections for p+H and stopping power for p in Al

Intermediate regime

All the elementary processes max

\[ K \sim 1 \]

To go beyond p+H
the collisional strength parameter:

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

Strong interaction regime

Perturbative regime

\[ V_p = V_e \]

Energy (keV)
Research program of the FISIC project

**Fast Ion - Slow Ion Collisions**

barely known when ion stopping power is maximum while one of the widespread phenomena in the universe and the least studied in laboratory!!

- in plasmas
  - stellar and interstellar

![Image of plasmas and stellar and interstellar phenomena](image.png)
Research program of the FISIC project

Fast Ion - Slow Ion Collisions

barely known when ion stopping power is maximum while one of the widespread phenomena in the universe and the least studied in laboratory!!

☆ in plasmas
  ▶ stellar and interstellar
  ▶ inertial confinement fusion
Research program of the FISIC project

Fast Ion - Slow Ion Collisions

barely known when ion stopping power is maximum while one of the widespread phenomena in the universe and the least studied in laboratory!!

- in plasmas
  - stellar and interstellar
  - inertial confinement fusion

- in ion-matter interaction

![Graph showing relative dose distribution for X-rays, protons, and carbon ions in tissue penetration depth.](image-url)
Research program of the FISIC project

Fast Ion - Slow Ion Collisions

Experimentally: ions through plasma cells &....

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

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


challenging experiments & limited to specific systems
Research program of the FISIC project

**Recent progress**

Theoretically: **barely spare theoretical calculations**

- **Extension of the validity domain of non-perturbative methods**

**Coll. INSP & LCPMR**

**“Emergence”**
FISIC: a collider project on SPIRAL2 for Atomic Physics

✓ reach the “pure” 3 body problem ≡ stringent test of theories

Theories only treat a 3-body (p → H) problem...

✓ explore the role of additional electron to quantify the effects of:
  - closure / opening of different channels
  - screening and antiscreening (electron – electron interaction)
  - multiple processes

✓ Ion-plasma interactions:
  plasma: ionization state(s) uncertain, several charge states
  ion-ion: well defined charge states

Requirement: need of high intensity beams

To tune the projectile (HE) and target (LE) charge state over a wide range up to bare ion on hydrogenic target for several Z_p and Z_t

High Energy Ion Beam from LINAG
From C to Ar ions (2 ≤ E ≤ 14.5 MeV/u)

Low Energy Ion Beam from ECR source
with E ≤ 20 q kV, 12 ≤ A ≤ 40 and 3 ≤ q ≤ Z
FISIC: a collider project on SPIRAL2 for Atomic Physics

Ion-ion collisions in the intermediate regime    Breakthrough in atomic collision physics

What do we need?

- a crossed-beam device

With high ion beam intensities, high optical quality

- control of the ionization state of both the projectile and target
  Ion-ion with well defined charge states

- investigation of a large variety of systems

Feasible with the avenue of SPIRAL2
Research program of the FISIC project

a complete experimental program

breakthrough in atomic collision physics

**FISIC**

**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 $3 \leq q \leq Z$
@ $E \leq 20 \text{ q kV}$

**S$^3$: Super Separator Spectrometer**

control of the electronic state on both the projectile and the target
FISIC project in the S3 room...

High Energy Ion Beam with charge Q+

INSP/GANIL/ GSI

f Selection of the desired Q+...
Stripper thickness...resistance ?

INSP/ Irfu/ GSI

Low Energy Ion Beam with charge q+

Collider & detection systems

Beam Dump FISIC (5kW max)

High Energy detection

Tech. Issues
### Ion beams for FISIC

We need to strip the SPIRAL2 ion beam!

<table>
<thead>
<tr>
<th>Ion(s)</th>
<th>Energy Range MeV/u</th>
<th>Maximum Intensity (pµA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}^{4+}$</td>
<td>5-7</td>
<td>$\geq 10^{**}$</td>
</tr>
<tr>
<td>$^{18}\text{O}^{6+}$</td>
<td>5-7</td>
<td>$\geq 10^{**}$</td>
</tr>
<tr>
<td>$^{22}\text{Ne}^{8+}$</td>
<td>5-7</td>
<td>$\geq 10^{**}$</td>
</tr>
<tr>
<td>$^{40}\text{Ar}^{14+}$</td>
<td>4-5</td>
<td>$\geq 10^{**}$</td>
</tr>
<tr>
<td>$^{28-30}\text{Si}^{10+}$</td>
<td>5-7</td>
<td>$\geq 10^{**}$</td>
</tr>
<tr>
<td>or $^{32-36}\text{S}^{12+}$</td>
<td>5-7</td>
<td>$\geq 10^{**}$</td>
</tr>
<tr>
<td>$^{40}\text{Ca}^{14+}$</td>
<td>5-7</td>
<td>$\geq 10^{**}$</td>
</tr>
<tr>
<td>$^{48}\text{Ca}^{16+}$</td>
<td>5-7</td>
<td>$\geq 10^{**}$</td>
</tr>
<tr>
<td>$^{58}\text{Ni}^{18+}$</td>
<td>4-14</td>
<td>$\geq 1^{**}$</td>
</tr>
</tbody>
</table>

**Ion beams with A/q=3**

$0.75 \text{ MeV/u} \leq E \leq 14.5 \text{ MeV/u}$
Ion beams for FISIC
Collision systems of interest for FISIC

To explore the unknown regime of “intermediate velocity” where ion stopping power is maximum

\[ K = \frac{V_e}{V_p} \times \frac{Z_t}{Z_p} \approx 1 \]

.....ideally..........

<table>
<thead>
<tr>
<th>Projectiles</th>
<th>The energy range for all the projectile/target combinations for all the shells</th>
<th>The energy range for all the projectile/target combinations for the K-shell processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(^{6+,5+,4+})</td>
<td>0.9 to 8.1</td>
<td>0.9 to 8.1</td>
</tr>
<tr>
<td>O(^{8+,7+,6+})</td>
<td>1.2 to 8.1</td>
<td>1.2 to 8.1</td>
</tr>
<tr>
<td>Ne(^{10+,9+,8+})</td>
<td>0.6 to 8.1</td>
<td>1.2 to 8.1</td>
</tr>
<tr>
<td>Ar(^{18+,17+,16+,15+,14+})</td>
<td>0.6 to 8.1</td>
<td>2.5 to 8.1</td>
</tr>
<tr>
<td>Ni(^{28+,27+,......18+})</td>
<td>0.6 to 14.5</td>
<td>8.1 to 14.5</td>
</tr>
</tbody>
</table>

Targets, up to one e- or fully stripped

N, O, Ne, Ar
SPIRAL2 Ion Beam Stripping: Calculations performed with the ETACHA Code

Ne$^{8+}$ beam
SPIRAL2 Ion Beam Stripping: Calculations performed with the ETACHA Code

**Ar^{14+} beam**
SPIRAL2 Ion Beam Stripping: Calculations performed with the ETACHA Code

Ni\(^{18+}\) beam

**8.1 MeV/u**

- Black: 28
- Red: 27
- Blue: 26
- Pink: 25
- Light green: 24
- Green: 23
- Light blue: 22
- Cyan: 21
- Purple: 20
- Brown: 19
- Yellow: 18

**14.5 MeV/u**

- Black: 28
- Red: 27
- Blue: 26
- Pink: 25
- Light green: 24
- Green: 23
- Light blue: 22
- Cyan: 21
- Purple: 20
- Brown: 19
- Yellow: 18
SPIRAL2 Ion Beam Stripping: Calculations performed with the ETACHA Code

<table>
<thead>
<tr>
<th>projectile</th>
<th>% particles</th>
<th>C thickness [μg/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8+</td>
<td>9+</td>
</tr>
<tr>
<td>Ne @ 1.2 MeV/u</td>
<td>46</td>
<td>21</td>
</tr>
<tr>
<td>Ne @ 1.6 MeV/u</td>
<td>42</td>
<td>34</td>
</tr>
<tr>
<td>Ne @ 2.5 MeV/u</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>Ne @ 2.5 MeV/u</td>
<td>18</td>
<td>43</td>
</tr>
<tr>
<td>Ne @ 8.1 MeV/u</td>
<td>17</td>
<td>48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>projectile</th>
<th>% particles</th>
<th>C thickness [μg/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14+</td>
<td>15+</td>
</tr>
<tr>
<td>Ar @ 2.0 MeV/u</td>
<td>29</td>
<td>20</td>
</tr>
<tr>
<td>Ar @ 2.5 MeV/u</td>
<td>24</td>
<td>30</td>
</tr>
<tr>
<td>Ar @ 8.1 MeV/u</td>
<td>1.4</td>
<td>17</td>
</tr>
<tr>
<td>Ar @ 8.1 MeV/u</td>
<td>0.1</td>
<td>2.6</td>
</tr>
<tr>
<td>Ar @ 8.1 MeV/u</td>
<td>0.01</td>
<td>0.34</td>
</tr>
</tbody>
</table>

For both projectiles e-...
## SPIRAL2 Ion Beam Stripping: Calculations performed with the ETACHA Code

### Projectile and % Particles

<table>
<thead>
<tr>
<th>Projectile</th>
<th>18+</th>
<th>19+</th>
<th>20+</th>
<th>21+</th>
<th>22+</th>
<th>23+</th>
<th>24+</th>
<th>25+</th>
<th>26+</th>
<th>27+</th>
<th>28+</th>
<th>C Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni @ 2.0 MeV/u</td>
<td>18</td>
<td>22</td>
<td>20</td>
<td>12</td>
<td>5</td>
<td>1.4</td>
<td>0.2</td>
<td>0.02</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>&gt;= 20</td>
</tr>
<tr>
<td>Ni @ 2.2 MeV/u</td>
<td>15</td>
<td>22</td>
<td>23</td>
<td>17</td>
<td>8</td>
<td>2.8</td>
<td>0.6</td>
<td>0.06</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>&gt;= 20</td>
</tr>
<tr>
<td>Ni @ 4.9 MeV/u</td>
<td>0.4</td>
<td>2.4</td>
<td>8.7</td>
<td>20</td>
<td>28</td>
<td>24</td>
<td>12</td>
<td>3.1</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Ni @ 4.9 MeV/u</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>1.5</td>
<td>6.5</td>
<td>19</td>
<td>33</td>
<td>29</td>
<td>10</td>
<td>0.34</td>
<td>0</td>
<td>&gt;= 100</td>
</tr>
<tr>
<td>Ni @ 8.1 MeV/u</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>1.2</td>
<td>8.6</td>
<td>31</td>
<td>45</td>
<td>12</td>
<td>1.1</td>
<td>0</td>
<td>&gt;= 400</td>
</tr>
<tr>
<td>Ni @ 14.5 MeV/u</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.4</td>
<td>4</td>
<td>19</td>
<td>40</td>
<td>33</td>
<td>3</td>
<td>0.1</td>
<td>100</td>
</tr>
<tr>
<td>Ni @ 14.5 MeV/u</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.98</td>
<td>14</td>
<td>66</td>
<td>18</td>
<td>1.3</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>Ni @ 14.5 MeV/u</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>4</td>
<td>31</td>
<td>45</td>
<td>19</td>
<td>19</td>
<td>&gt;= 1000</td>
</tr>
<tr>
<td>Ni @ 14.5 MeV/u</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>3</td>
<td>23</td>
<td>45</td>
<td>28</td>
<td>&gt;= 2200</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Projectile</th>
<th>18+</th>
<th>19+</th>
<th>20+</th>
<th>21+</th>
<th>22+</th>
<th>23+</th>
<th>24+</th>
<th>25+</th>
<th>26+</th>
<th>27+</th>
<th>28+</th>
<th>Al Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni @ 14.5 MeV/u</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.26</td>
<td>2.6</td>
<td>15</td>
<td>43</td>
<td>32</td>
<td>7.5</td>
<td>&gt;=750</td>
</tr>
</tbody>
</table>

**Loss of ion charge states in the beam dump in some cases more than 50% in a single shutter**
FISIC in $S^3$ (Super Spectrometer Separator)

Stripping

Rotation speed up to 3000 rpm

Tests in June 2011 and 2012 on LISE2000

$^{129}$Xe – 7.5 MeV/u – up to 5 µAe

Resistance of targets under beam impact

2D thermal simulations: Tahir et al NIMB 276 (2012)

10 MeV/u O$^{6+}$ beam (1.4 pµA) on 100 µg/cm$^2$ Al

Saturation of $T$ (< $T_{\text{melting}}$) due to heat conduction and radiation losses from the heated material.
FISIC project in the S3 room...

Charge state selection of the high energy ion beam;

Coll. INSP, Irfu, GSI, GANIL

meetings in May and June 2014 on material desorption

impact on vacuum

experiments @ GSI, summer 2014

preliminary results W/Cu thin sample
FISIC project in the S3 room...

Charge state selection of the high energy ion beam;
Coll. INSP, Irfu, GSI, GANIL

for FISIC use of shutters

Upstream BD

Longitudinal BD

Downstream BD

preliminary results W/Cu thick sample

meetings in May and June 2014 on material desorption

impact on vacuum

experiments @ GSI, summer 2014
FISIC project in the S3 room...

Within the ANR/DFG contract
Coll. INSP, CIMAP, HI Jena, GSI

Status

10⁻⁹ mbar

Collider & detection systems

chamber & detection systems

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

The FISIC project will offer the unique opportunity to access hitherto unexplored domain of ion-ion collisions

*Of fundamental importance for atomic physics as well as of great relevance for plasma physics and ion-matter interaction*

One of the technical challenges:
stripping of high intensity beams at specific energies
optimal choice of the stripper (material, thickness, resistance)
estimation of the losses in the beam dump (resistance, desorption)

Carbon strippers with mass thickness ~20-2000 µg/cm² are needed to get all the desired charge states

*The technical realization and resistance to the high beam intensities have to be tested!*
the FISIC project
An update of the collaboration

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H. Braeunig
S. Hagmann
U. Spillmann
N. Tahir et al.
Th. Stöhlker

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B. Kindler
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C. Hahn
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