ATOMIC PHYSICS OF FAST ION – SLOW ION COLLISIONS: THE FISIC PROJECT @SPIRAL2

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CIMAP
Helmholtz Gemeinschaft
GSI
SPARC

- the main scientific goals and motivations
- a status report of the project on SPIRAL2

Projet financé par l'ANR – Project funded by the ANR
DFG

THE FISIC PROJECT

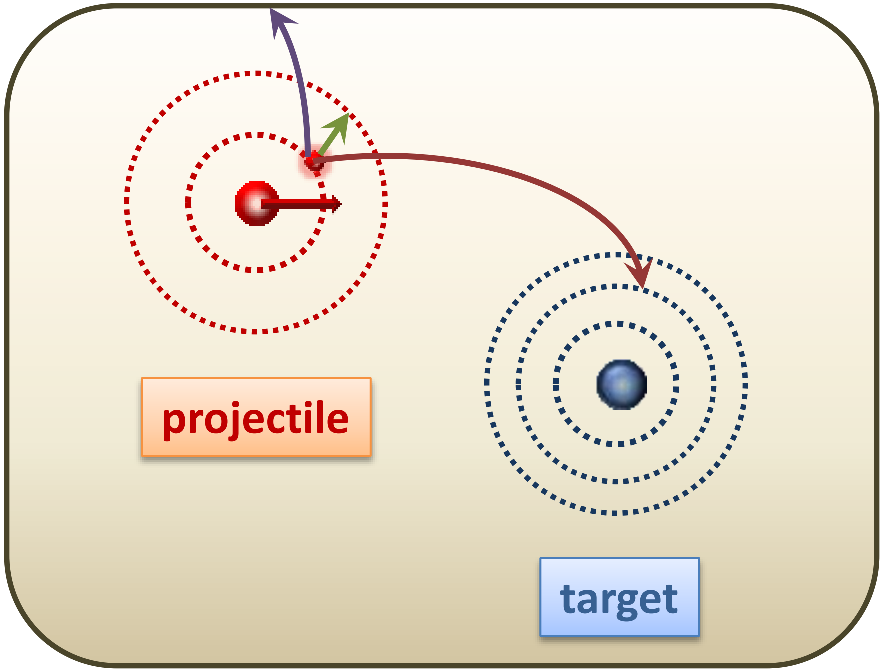
The main goals

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



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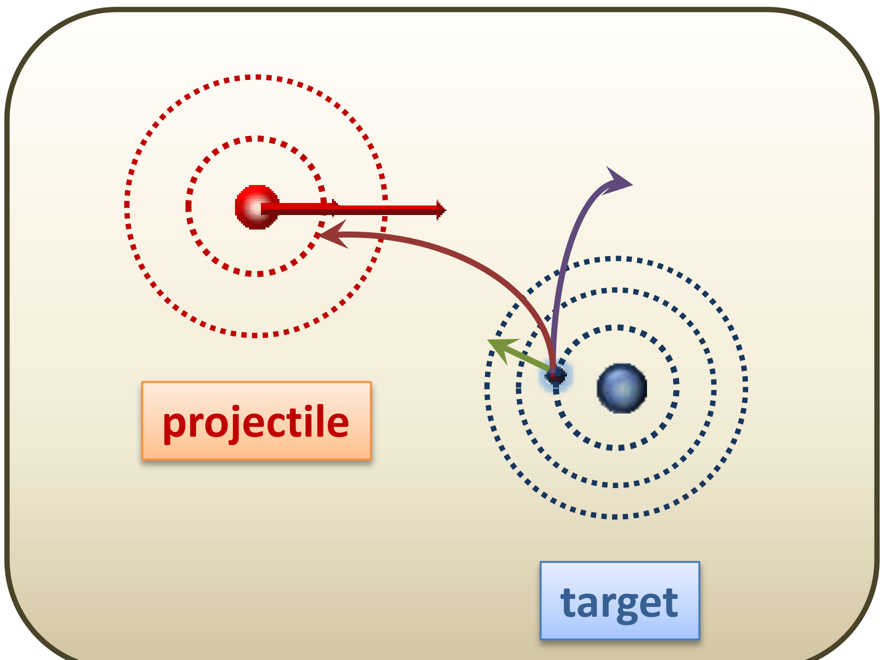

ionization , excitation , capture

exploration of the collision regimes:

V_p Z_t Z_p

$$K = \frac{v_e}{v_p} \times \frac{Z_t}{Z_p}$$

(for projectile electrons)

K >>1 **K ~ 1** **K <<1**

non-pertubative.........to.......... pertubative regime

intermediate regime

THE FISIC PROJECT

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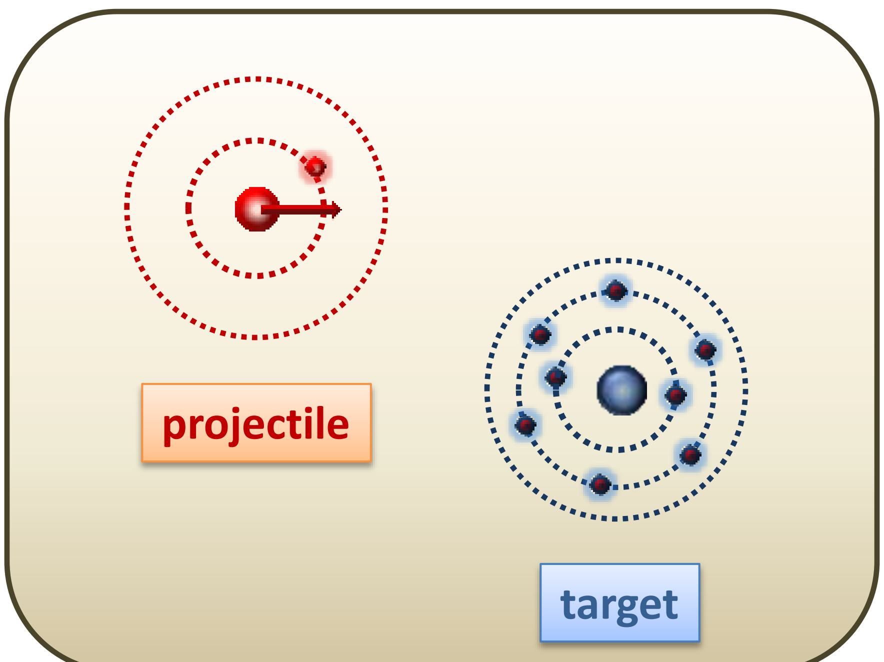
for N-body systems

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**

$\kappa \sim 1$

THE FISIC PROJECT

The main goals

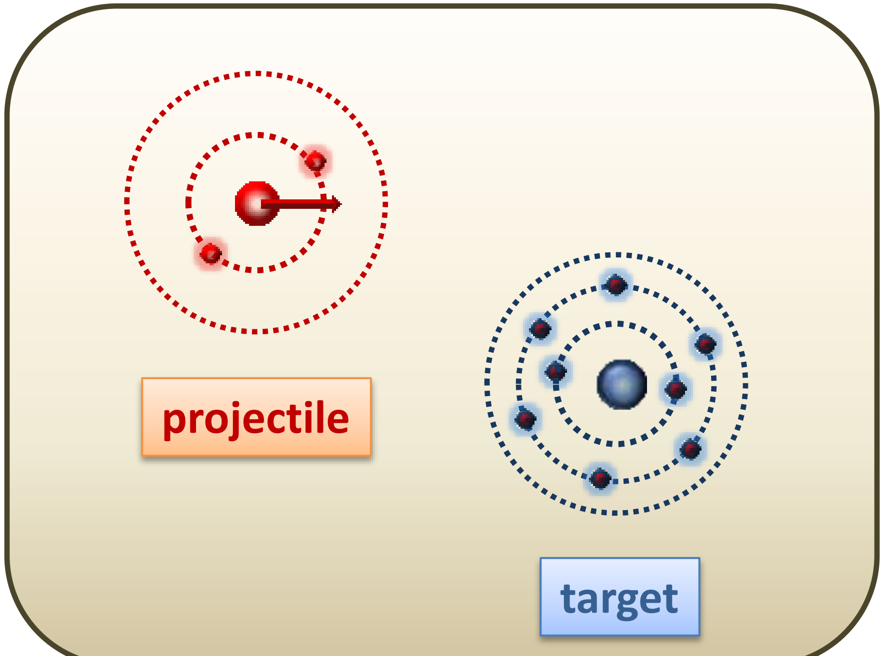
Controlling the projectile and target orbital occupation……

in Fast Ion - Slow Ion Collisions

for a wide range of collision systems , i.e. Zp & Zt

From 3- to N-body systems

- **to benchmark the theoretical approaches**
- **to explore the role of additional electrons – one by one –**



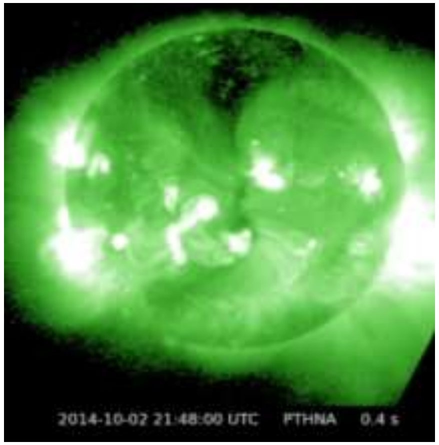
- tuning closure of different channels
- effects of electron – electron interactions
- multiple processes… often neglected !
- role of Coulomb forces

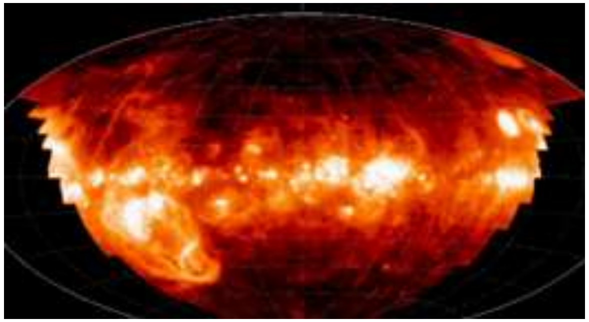
THE FISIC PROJECT

motivations

Cross sections of electronic processes in ion-ion collisions barely known when ion stopping power is maximum

- in plasmas
  - stellar and interstellar





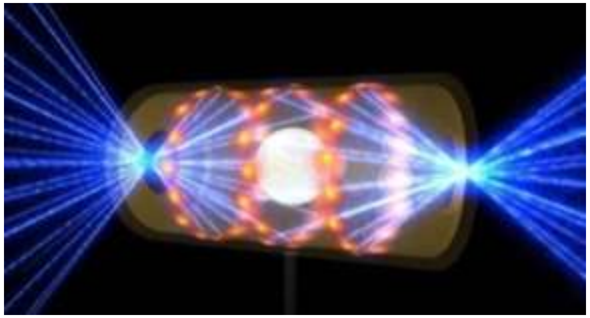
THE FISIC PROJECT

motivations

Fast Ion - Slow Ion Collisions

barely known when ion stopping power is maximum

- in plasmas
  - stellar and interstellar
  - inertial confinement fusion



Lawrence Livermore National Laboratory

THE FISIC PROJECT

motivations

Fast Ion - Slow Ion Collisions

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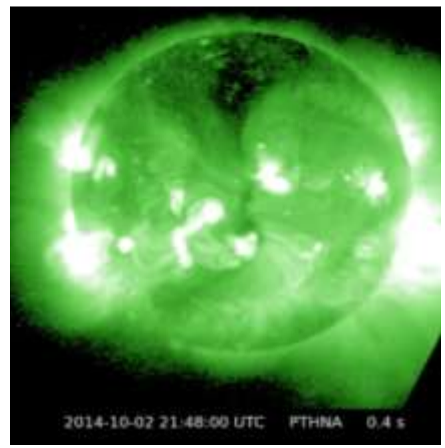
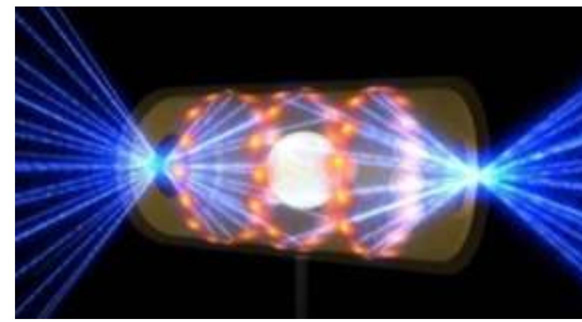
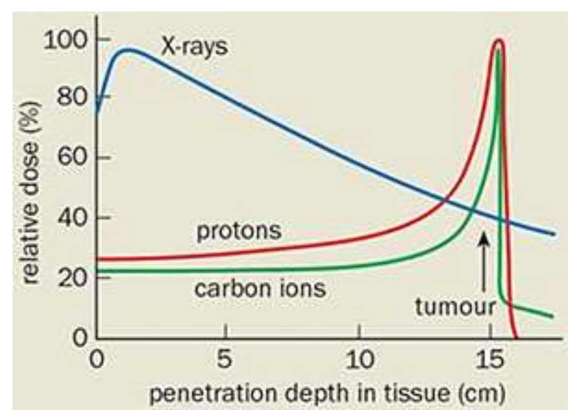
  - inertial confinement fusion





- in ion-matter interaction



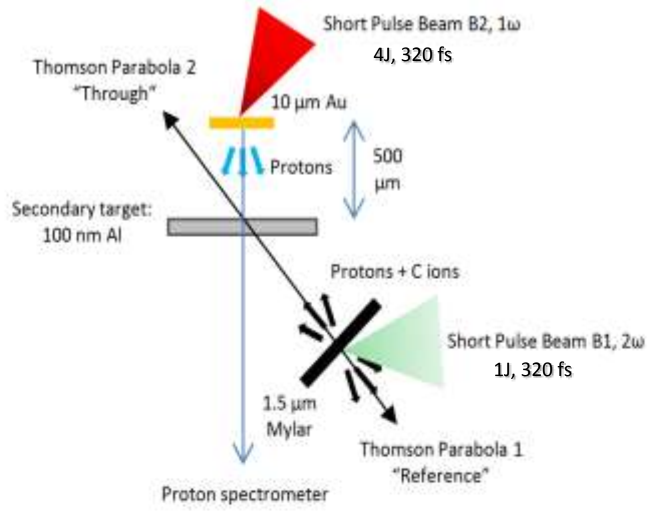
THE FISIC PROJECT

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

Phys. Rev. Lett., 110, 135003 (2013)

with perspectives towards XFEL for ultrafast isochoric heating up to 100 eV

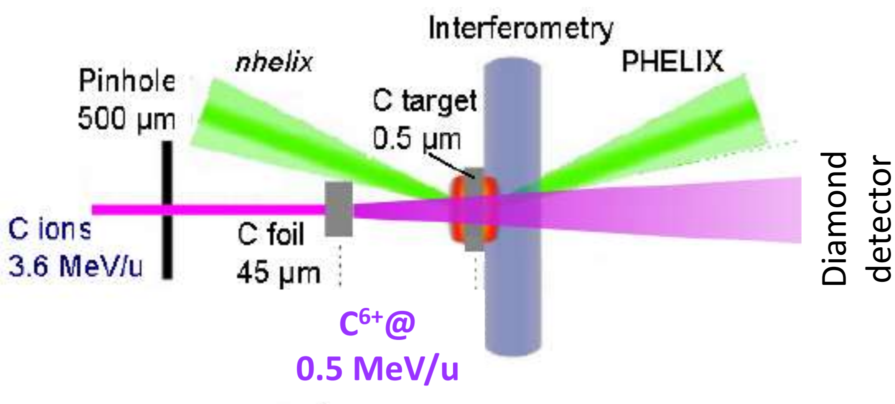
THE FISIC PROJECT

Recent progress

Fast Ion - Slow Ion Collisions

Experimentally: ions through plasmas…

• Ion energy loss measurement in a laser-generated carbon plasma ($N_e=10^{21}$ cm^{-3}, $T_e$max ~180 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)

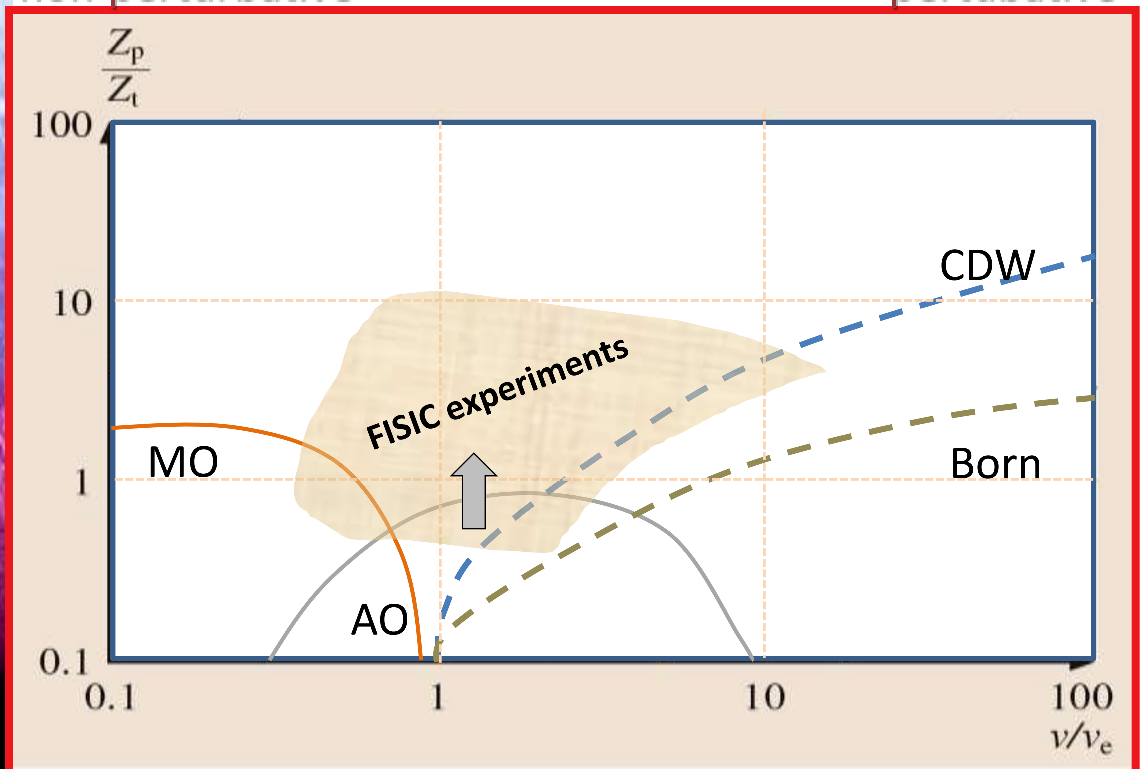
➡ challenging experiments & limited to specific systems

THE FISIC PROJECT

Recent progress

Theoretically :

non-perturbative pertubative



Extension of the validity domain of non-perturbative methods

Coll. INSP & LCPMR

"Emergence" UPMC SORBONNE UNIVERSITÉS

Labex MiChem SORBONNE UNIVERSITÉS

THE FISIC PROJECT

a complete experimental program

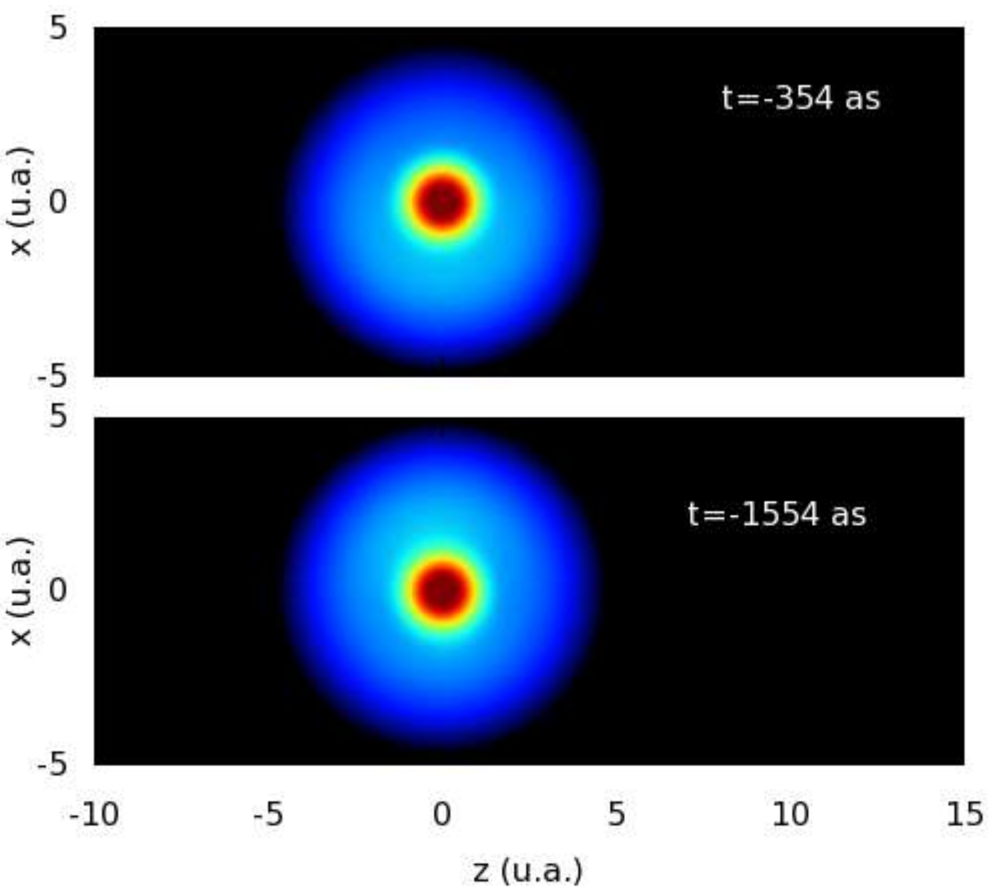
Recent progress

Theoretically : Extension of the validity domain of non-perturbative methods

Coll. INSP & LCPMR

"Emergence" UPMC

G. Labaight, PhD UPMC, Sept. 2014



H^+ on Li (3 e- system)

@ 4 keV/u

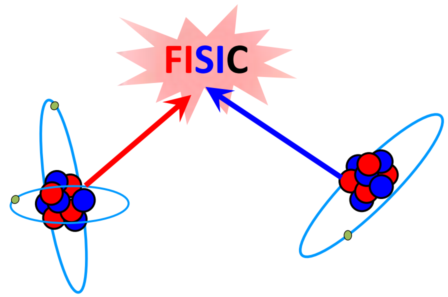
K>>1

@ 80 keV/u

K<1

THE FISIC PROJECT: WHAT IS NEEDED ?

❑ **a crossed-beam device**



For instance :
Ar^{Q+} + Ar^{q+} @ 8MeV/u

❑ **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

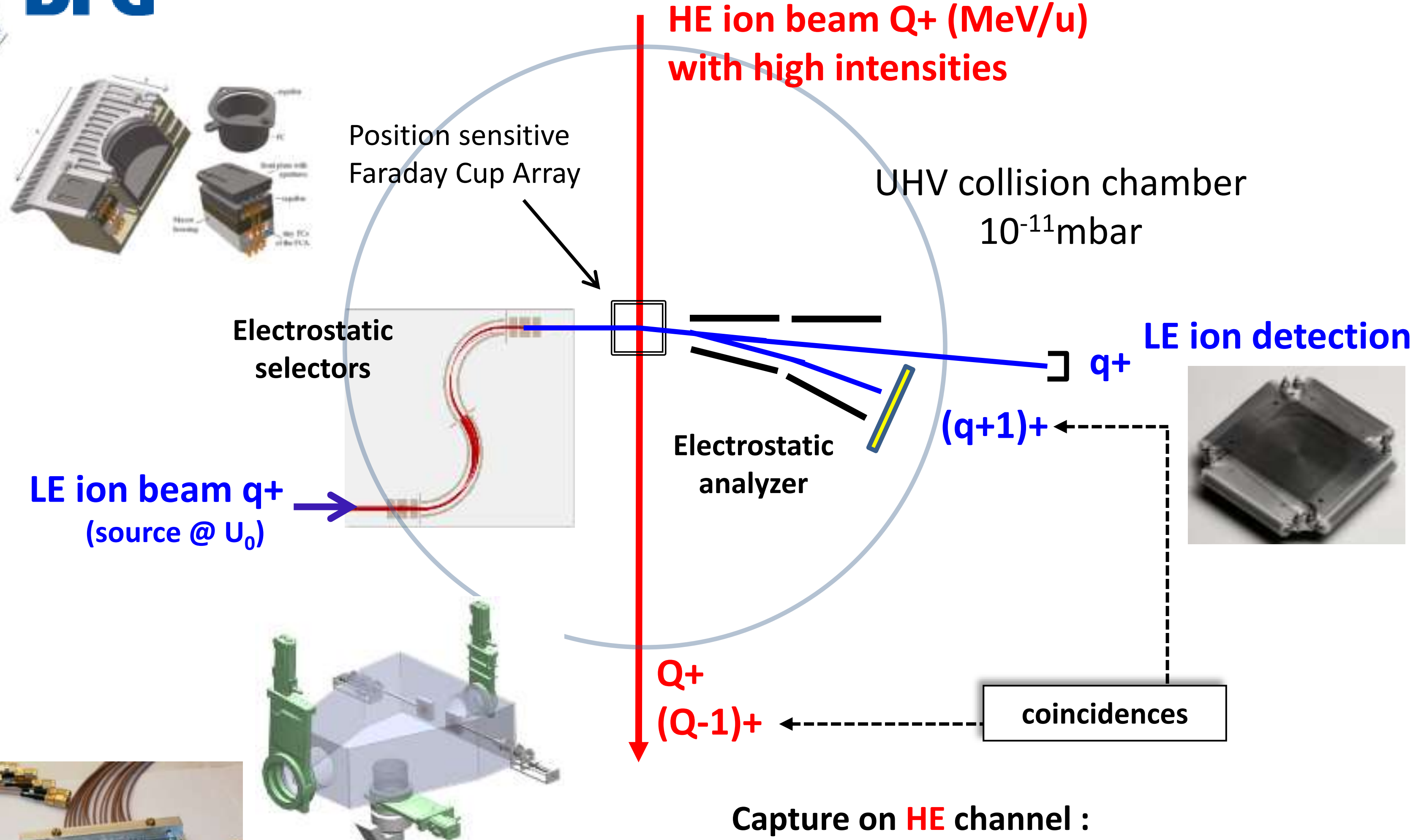
❑ **Projectiles:** **high energy ion beams (MeV/u)** **with high intensities** (10^{12}-10^{13} sec^{-1})**, good optical quality and perfect selection of the ion charge state**

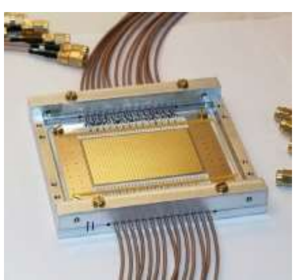
❑ **Coincidence measurements : projectile/target charge changes, X/ ion**

❑ **Efficient detection systems**

THE FISIC PROJECT

Charge exchange cross section measurements for the day-one experiment





HE ion detection
also at CRYRING/FAIR

Capture on HE channel :

$$Ar^{18+} + Ar^{q+} \rightarrow Ar^{17+} + Ar^{(q+1)+}$$

Ionization on LE channel :

$$Ar^{18+} + Ar^{q+} \rightarrow Ar^{18+} + Ar^{(q+1)+} + e^-$$

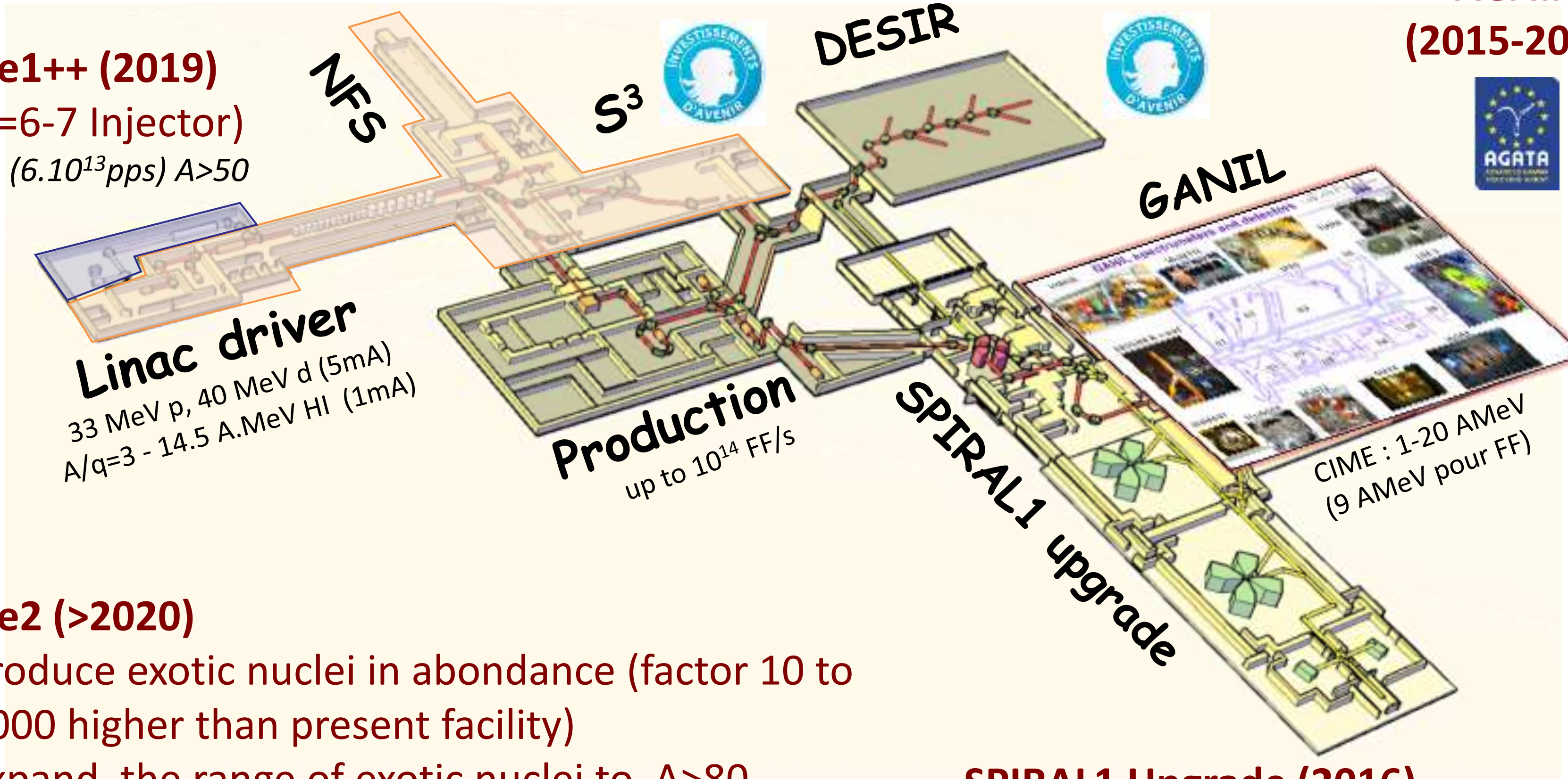
A National & EU priority

Phase1 (2015)
Increase the intensity of stable beams by a factor 10 to 100 – High intense neutron source
10pμA (6.10^13pps) A<50

DESIR Phase1+ (2018)
(low energy facility)

AGATA (2015-2018)

Phase1++ (2019)
(A/Q=6-7 Injector)
10pμA (6.10^13pps) A>50



Phase2 (>2020)
- Produce exotic nuclei in abondance (factor 10 to 1000 higher than present facility)
- Expand the range of exotic nuclei to A>80
- Post-acceleration of high intensity RIB

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**

Selection & Identification
➔Time of flight + Energy
➔ A measurement

Ground state measurement (gas catcher)
➔β/β–delayed
➔Laser spectroscopy
➔Mass measurement
➔Chemistry
PHASE 1

Beam dump for 99% of the beam

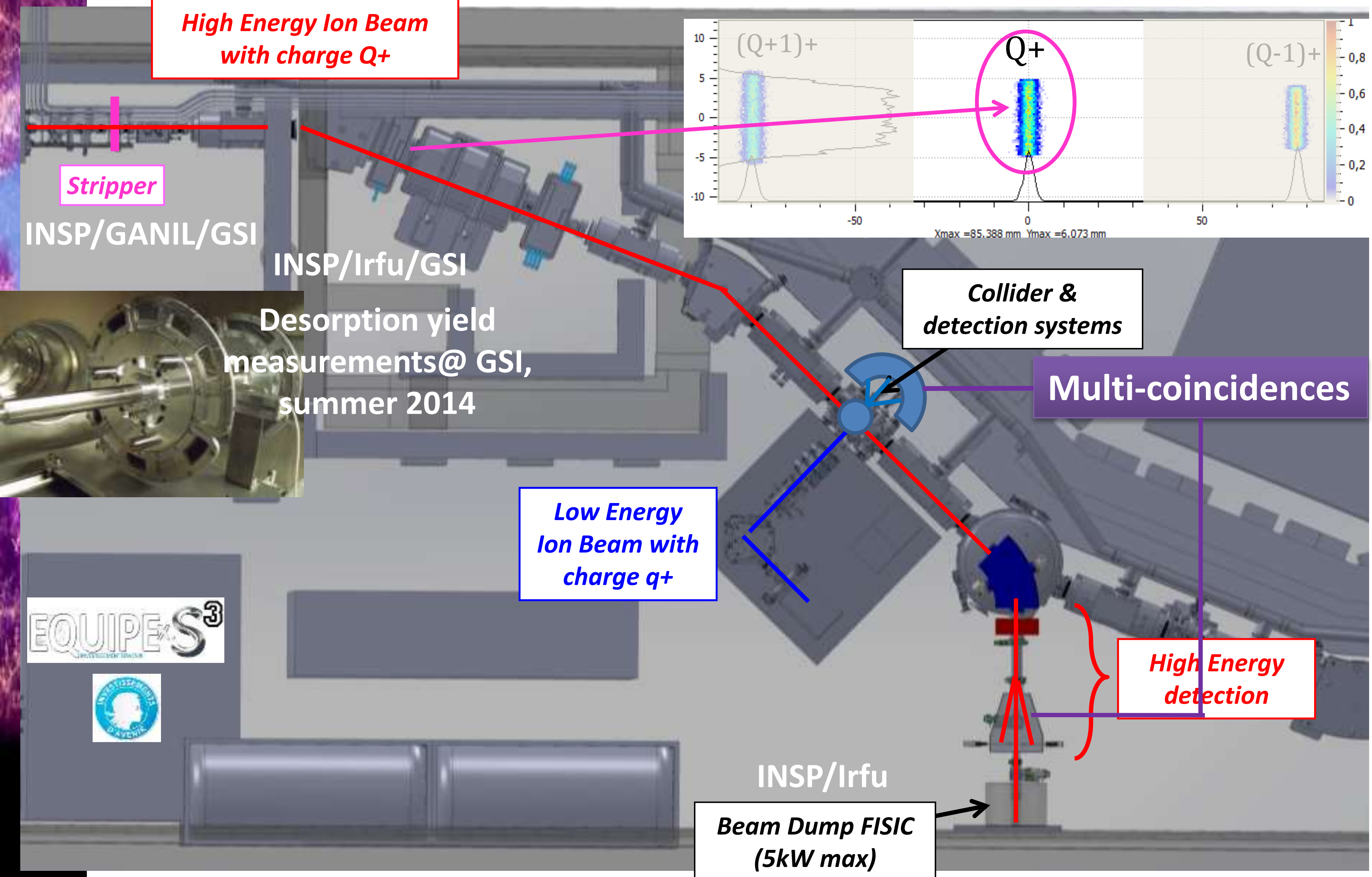
Two step reactions
➔Transfer+Fusion (transfer)

Specific Modes
➔ Ion-ion collision : **FISIC** Program
PHASE 2

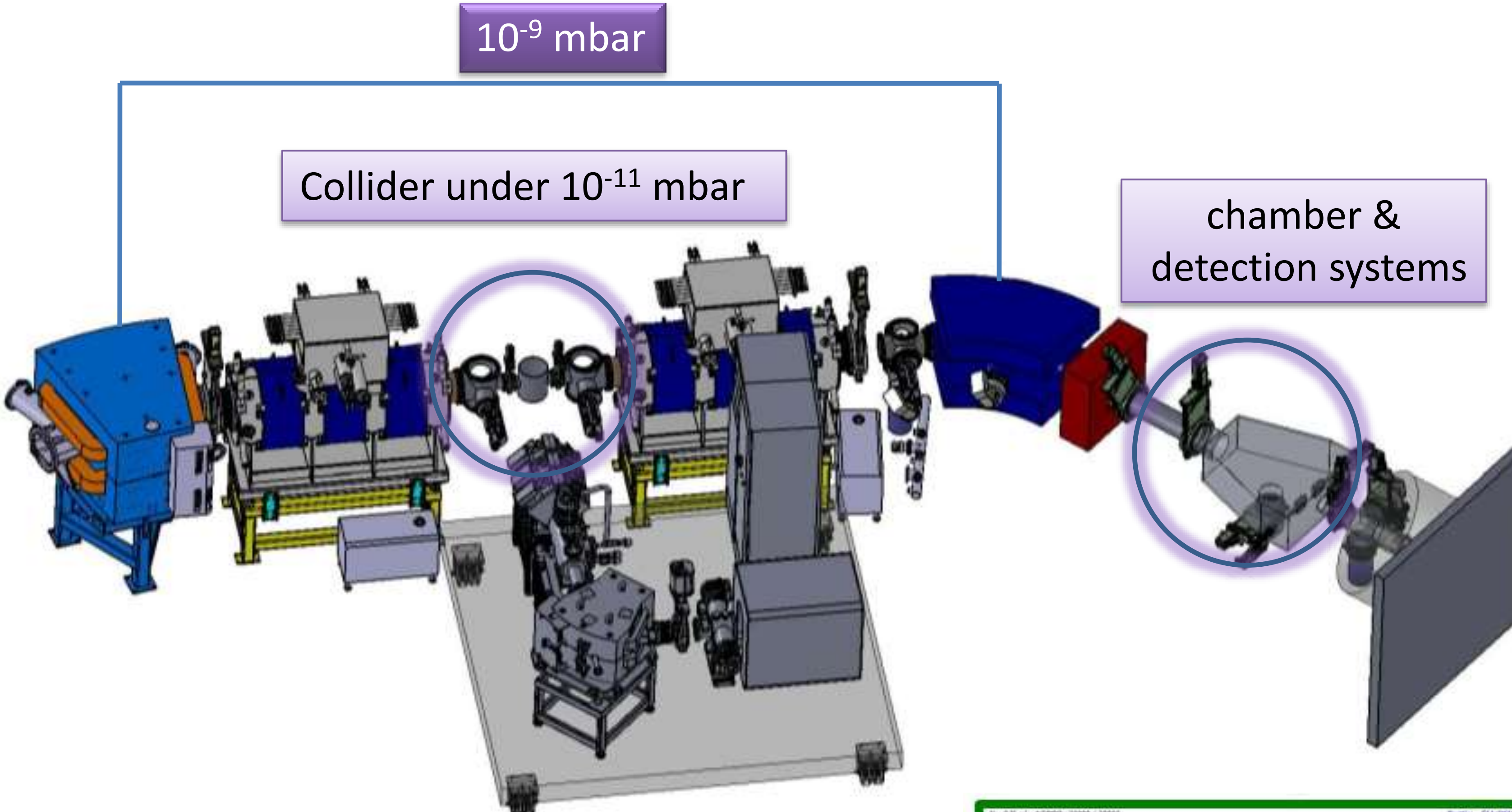
Delayed spectroscopy
➔ p, α, γ, e- decay
PHASE 0

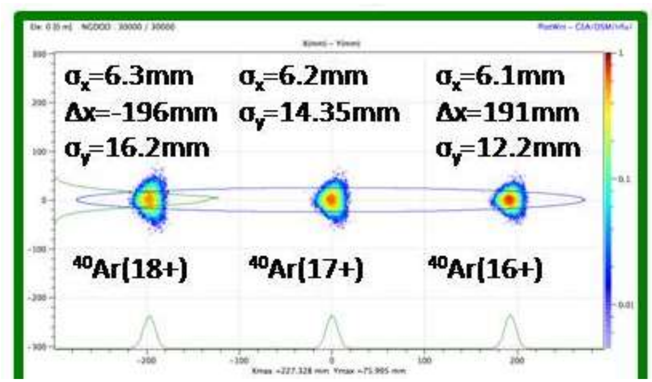
DESIR

THE FISIC PROJECT @S3/SPIRAL2



THE FISIC PROJECT @S3/SPIRAL2





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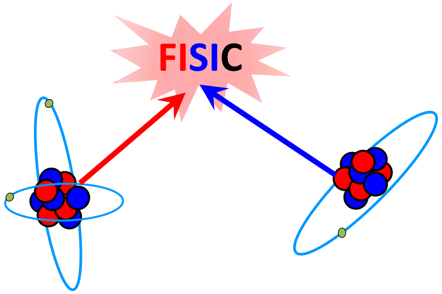


breakthrough in atomic collision physics

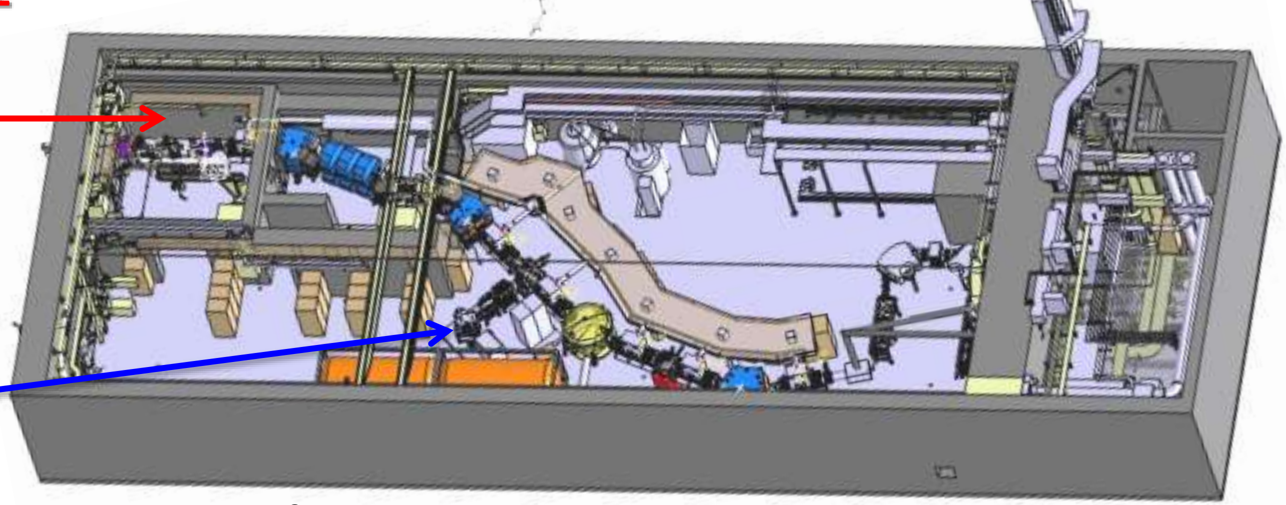
ANR-13-IS04-0007- Fit-FISIC

Kick-off meeting: March 2014

Fast Ions from SPIRAL2

from C to Ni ions

(0.75 ≤ E ≤ 14.5 MeV/u)



S^3: Super Separator Spectrometer

Slow Ions from an ECR source

with from C to Ar of 3 ≤ q ≤ Z

@ E ≤ 20 q kV

the FISIC project

An update of the collaboration

Status

CiMap

J Rangama
L. Adoui
J.-Y Chesnel
A Mery
P. Rousseau
J-M. Ramillon

INSP

E. Lamour
A. Levy
S. Macé
C. Prigent
J.-P. Rozet
S. Steydli
M. Trassinelli
D. Vernhet

GSI HELMHOLTZ GEMEINSCHAFT

A. Gumberidze
A. Braeuning-Demian
H. Braeuning
S. Hagmann
U. Spillmann
N. Tahir *et al.*
Th. Stöhlker
C. Hahn
T. Koeler
G. Weber

GANIL

R. Levallois
L Maunoury
H. Savajols
F. Lutton
C. Stodel

GSI

C. Trautmann
M. Bender
B. Kindler
K. Kupta
M. Tonut
D. Severin

Irfu

M. Authier
A. Drouart
O. Cloue

LCPMR

A. Dubois
J. Caillat

CAU Christian-Albrechts-Universität zu Kiel

L. Panitzsch *et al.*

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

A. Müller
S. Schippers
C. Brandau

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

Meeting with theorists, Sept. 2014

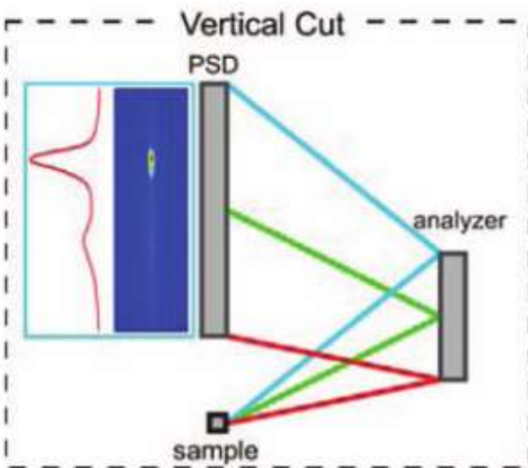
FISIC project in the S3 room…

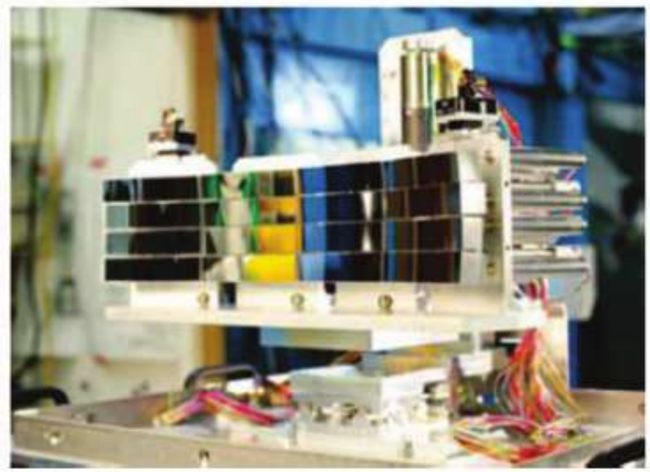
Status

Within the Plas@par Labex: new generation of X-ray spectrometer

Coll. INSP, LCPMR

PLAS@PAR
Plasmas à Paris





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

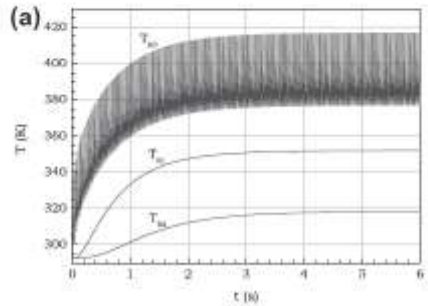
Possibility of X/ion coincidence measurements towards excitation processes

FISIC project in the S3 room…

Status

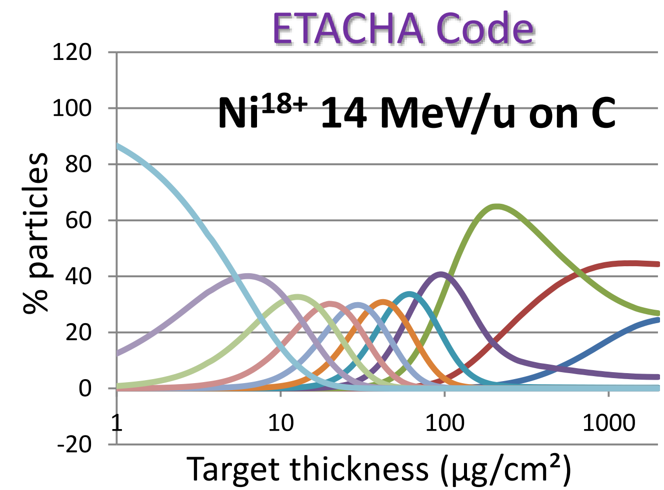
Stripping @high intensity ; Coll. INSP, GANIL, GSI

rotating wheel



2D simulations

NIM B **276** (2012) 66 & **290** (2012) 43



Collision systems available with injector A/q=3

	targets, 1+ to fully stripped			
	N	O	Ne	Ar
$C^{6+,5+,4+}$		0.75 to 8.2		
$O^{8+,7+,6+}$		1.2 to 8.2		
$Ne^{10+,9+,8+}$		1.2 to 8.2		
$Ar^{18+,17+,16+,15+,14+}$			2.5 to 8.2	
$Ni^{28+,27+,\ldots\ldots.18+}$				8.2 to 14.5

energy range Mev/u

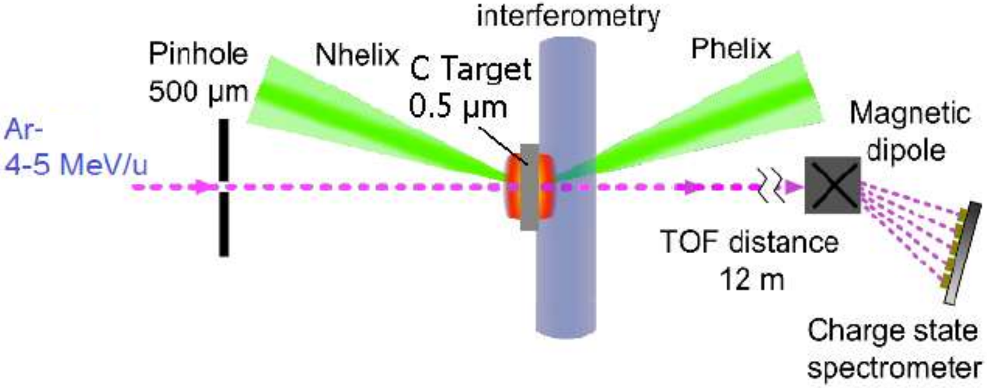
THE FISIC PROJECT

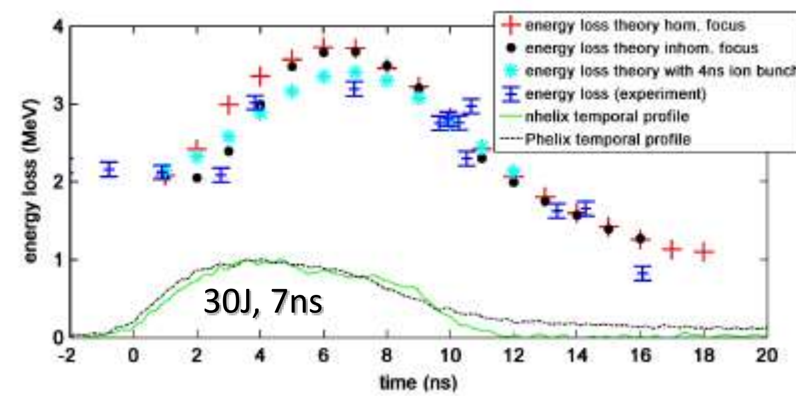
Recent progress

Fast Ion - Slow Ion Collisions

Experimentally: ions through plasmas…

• Ion energy loss at maximum stopping power in a laser-generated plasma in carbon foil ($N_e = 10^{21}$ cm^{-3}, $T_e$max ~180 eV)





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

Franck *et al* PRL110 (2013)

FISIC project in the S3 room…count rates and vacuum conditions

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

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

with D = 1 and z = 2mm

for the capture channel:
coincidence $Ar^{(Q-1)+}$ / $Ar^{(q+1)+}$

HE ion	σ_{capt} (cm²)	LE ion	I_2 (µAe)	σ_{ion} (cm²)	U (kV)	R_{capt} /s	R_{ion} /s	Back ground HE /s	Back ground LE /s	Δt (ns)	fortuitous coincidences
Ar^{18+}	$4.5\ 10^{-18}$	Ar^{4+}	5	$8\ 10^{-16}$	25=20+5	42	$7.4\ 10^{3}$	$4.8\ 10^{5}$	<2	24	7
Ar^{18+}	$4.5\ 10^{-18}$	Ar^{8+}	20	$1.8\ 10^{-16}$	20=15+5	66	$2.6\ 10^{3}$	$4.8\ 10^{5}$	0.04	14	2.5
Ar^{18+}	$3.5\ 10^{-18}$	Ar^{12+}	15	$4.7\ 10^{-17}$	10=20-10	30	400	$4.8\ 10^{5}$	0.002	10	0.4
Ar^{18+}	$1.6\ 10^{-18}$	Ar^{16+}	0.1	$1.5\ 10^{-18}$	1=20-19	0.19	0.18	$4.8\ 10^{5}$	10^{-11}	12	$1.7\ 10^{-4}$
Ar^{14+}	$1.5\ 10^{-18}$	Ar^{4+}	5	$8\ 10^{-16}$	25=20+5	18	$9.5\ 10^{3}$	$2.3\ 10^{5}$	<2	24	4.3

$P=10^{-9}$ 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

Ar^{Q+} (8MeV/u, I_1=50µA) + Ar^{q+} ($U=U_o-\Delta V$) → $Ar^{(Q-1)+}$ + $Ar^{(q+1)+}$

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Ar^{18+}	$4.5\ 10^{-18}$	Ar^{4+}	5	$8\ 10^{-16}$	25=20+5	42	$7.4\ 10^{3}$	$2.2\ 10^{7}$	<2	24	326 !!!
Ar^{18+}	$4.5\ 10^{-18}$	Ar^{8+}	20	$1.8\ 10^{-16}$	20=15+5	66	$2.6\ 10^{3}$	$2.2\ 10^{7}$	0.04	14	116 !!!
Ar^{18+}	$3.5\ 10^{-18}$	Ar^{12+}	15	$4.7\ 10^{-17}$	10=20-10	30	400	$2.2\ 10^{7}$	0.002	10	17 !!
Ar^{18+}	$1.6\ 10^{-18}$	Ar^{16+}	0.1	$1.5\ 10^{-18}$	1=20-19	0.19	0.18	$2.2\ 10^{7}$	10^{-11}	12	$7.8\ 10^{-3}$
Ar^{14+}	$1.5\ 10^{-18}$	Ar^{4+}	5	$8\ 10^{-16}$	25=20+5	18	$9.5\ 10^{3}$	$1.1\ 10^{7}$	<2	24	215 !!!

P=5$10^{-8}$ mbar over 7.5m

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

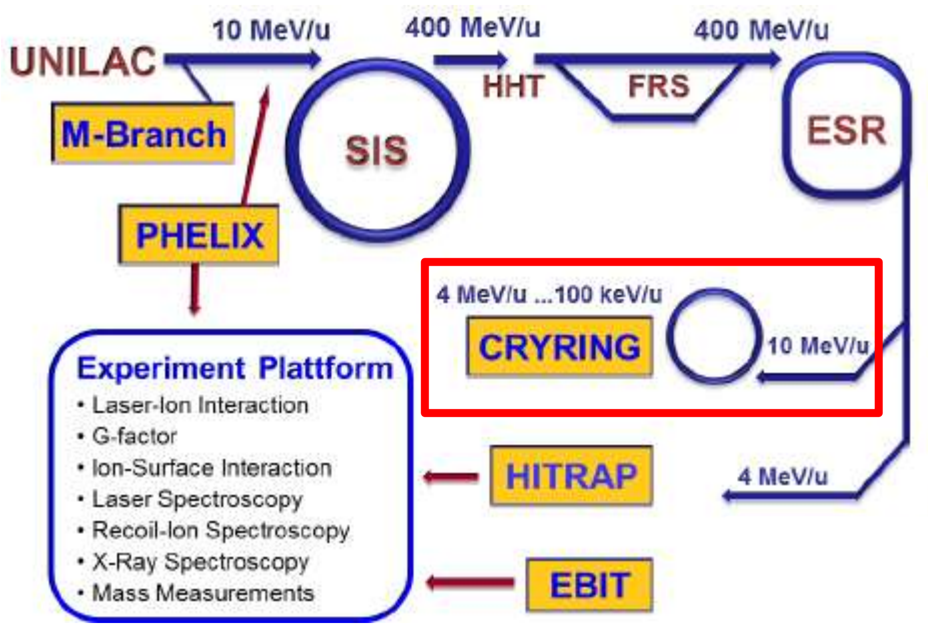
with 2ns of resolution

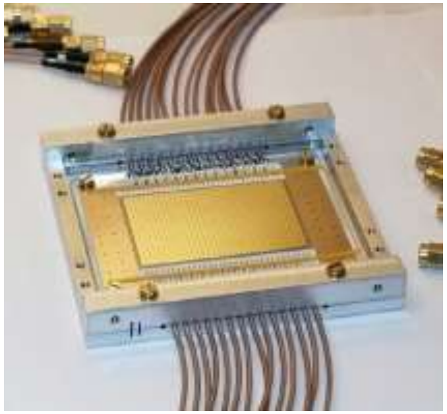
Among 5 physics cases, only one remains feasible with 5 10^{-8} mbar

vacuum in S3 => a crucial point

FISIC project in the S3 room... detections

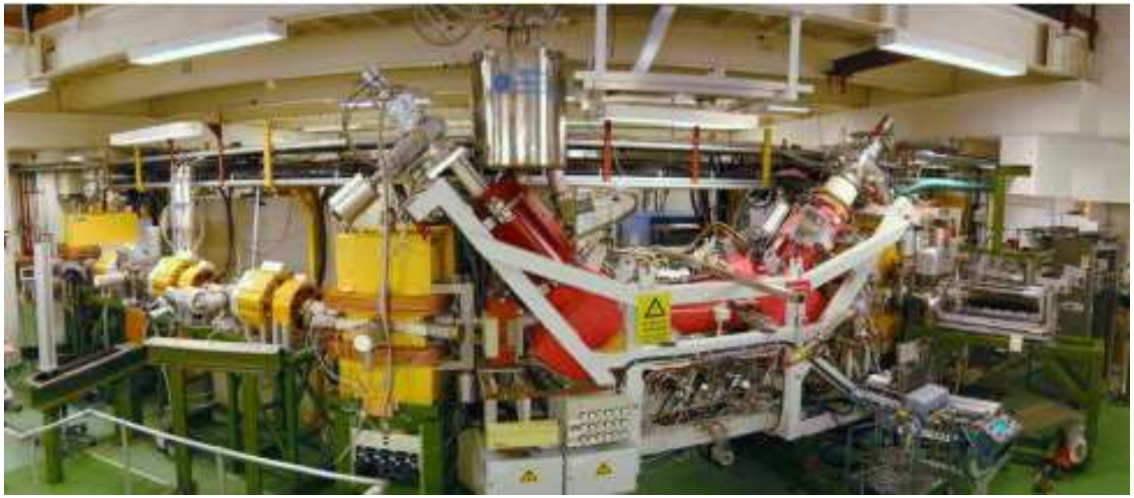
❑ HE ion detection system





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

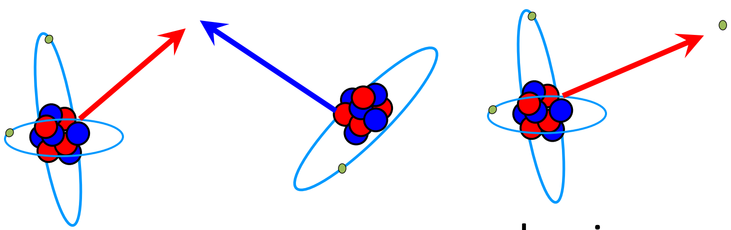
Tests of HE ion detectors at CRYRING in 2015

Atomic Physics in S3

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

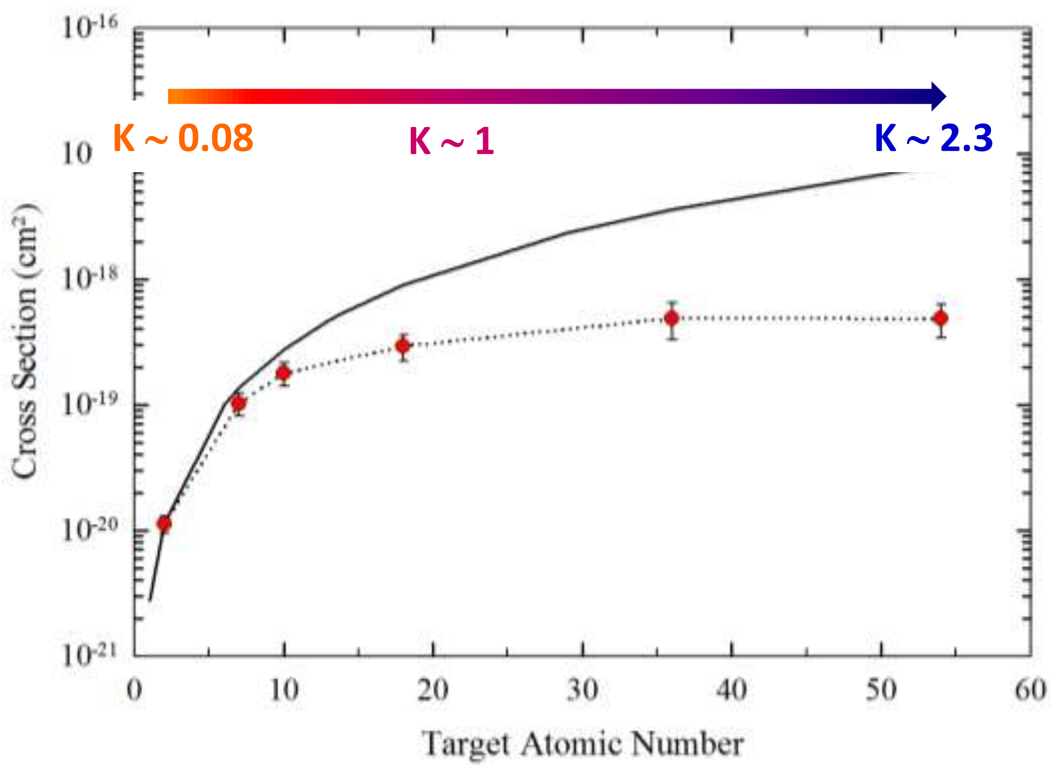
Fragmentation (Size, temperature, charge mobility effects)

Crossed beam experiments; (multi-)coincidence measurements

Studies in the intermediate collision regime

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

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



Perturbative calculation
Scaling law with Z_t^2

Compare to exp. data
strong decrease of σ_{exc}
more than one order of magnitude

Role of target electrons through e-e interactions

⇒ screening and antiscreening effects

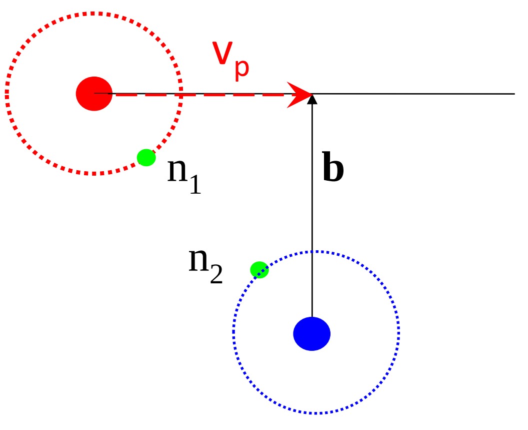
Studies in the intermediate collision regime

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

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

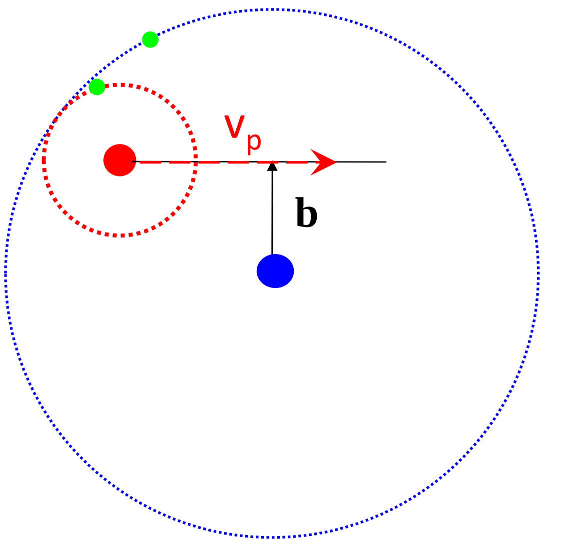
Screening and antiscreening effects / role of target electrons in ionization / excitation

large impact parameters (b)



screening is almost complete

small impact parameters (b)

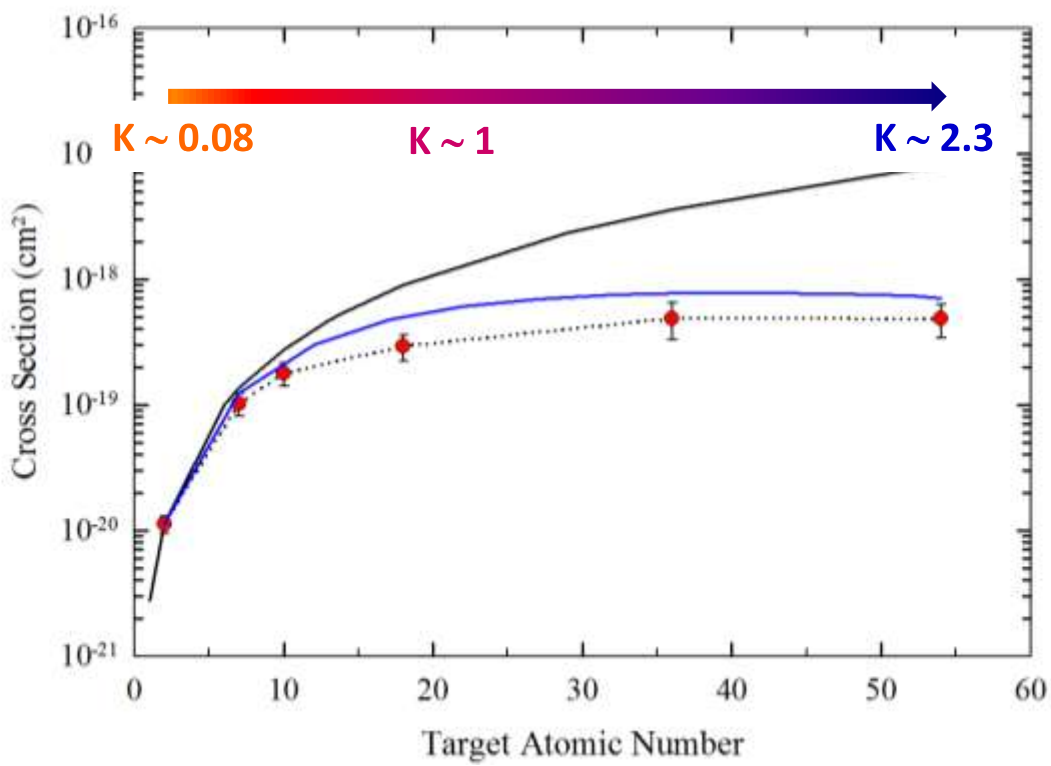


screening is very small but target e^- contribute to excitation or ionization (antiscreening)

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



Perturbative calculation
Scaling law with Z_t^2

Compare to exp. data
strong decrease of σ_{exc}
more than one order of magnitude

Role of target electrons through e-e interactions

⇒ screening and antiscreening effects

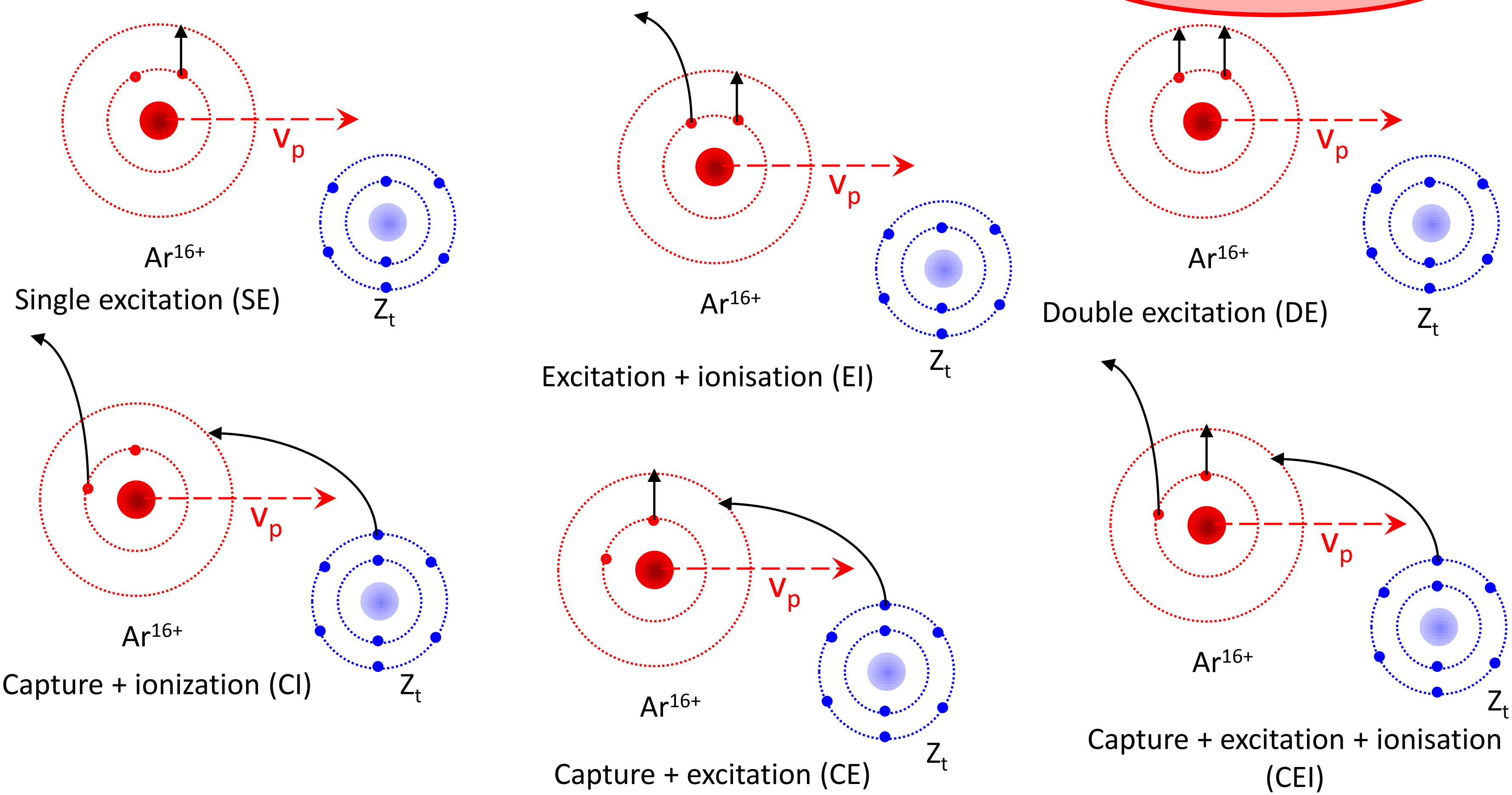
Symetric Eikonal calculations

Not tested for other conditions !

Studies in the intermediate collision regime

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

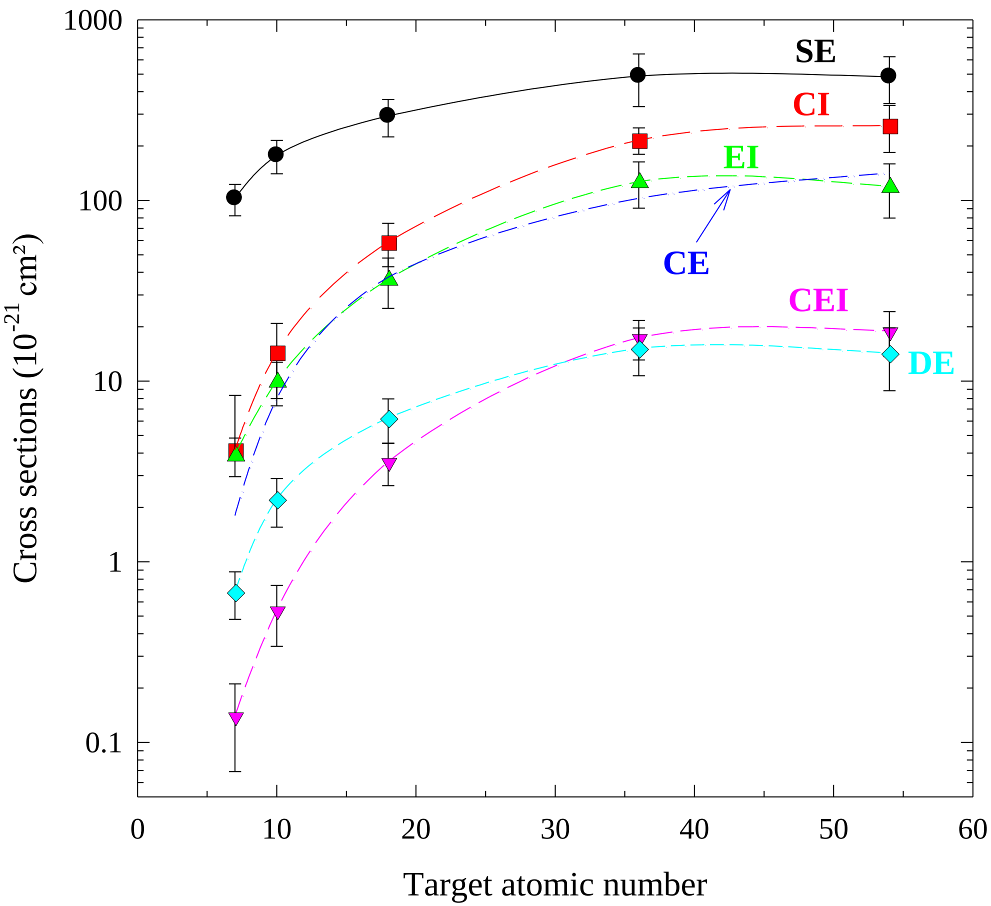
Possibility to isolate the single excitation process (1s→2p) from multiple processes



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 !