ENSAR2-NUPRASEN
Workshop on Nuclear Reactions

Overview on experimental aspects and needs for theory

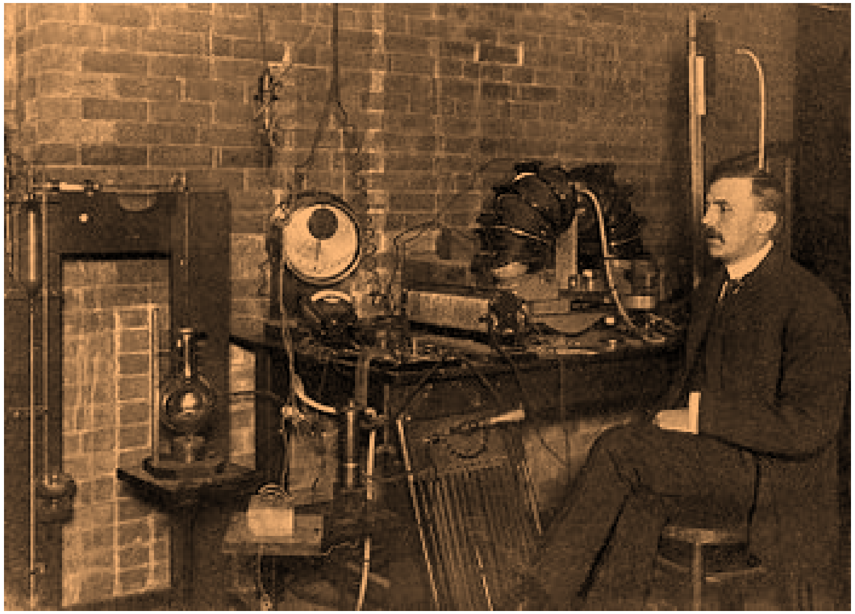
USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

D. Cortina
Universidad de Santiago de Compostela

Early Nuclear Reactions

Nuclear reactions are the process in which two nuclei collide to produce one or more nuclides that are different from the nuclide(s) that initiated the process.

→ they have been the subject of study since the early days of our field



- The earlier scattering experiments by Rutherford, Geiger and Marsden led to **important clues about atomic structure**
- The first observation of an induced nuclear reaction was achieved by Rutherford in 1919

$$^{14}N + \alpha \rightarrow {}^{16}O + p$$

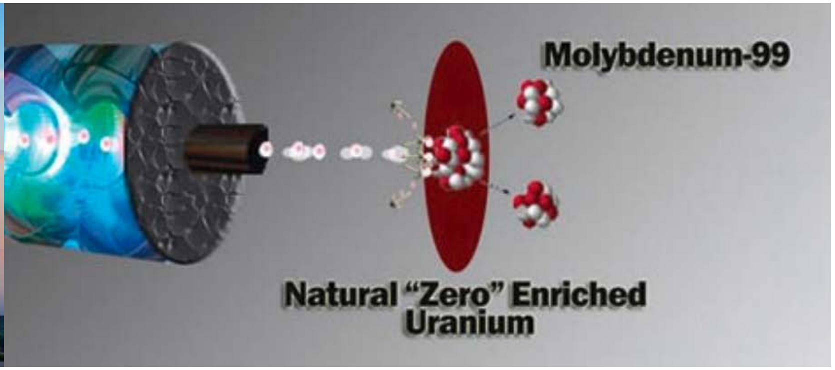
- In 1932 a fully artificial nuclear reaction was achieved by Cockcroft and Walton, who used artificially accelerated protons against ^{7}Li, to split the nucleus into two α particles.

Why Nuclear Reactions ?

To improve our knowledge of such a complex quantum system as it is the atomic nucleus and to exploit this knowledge for different applications

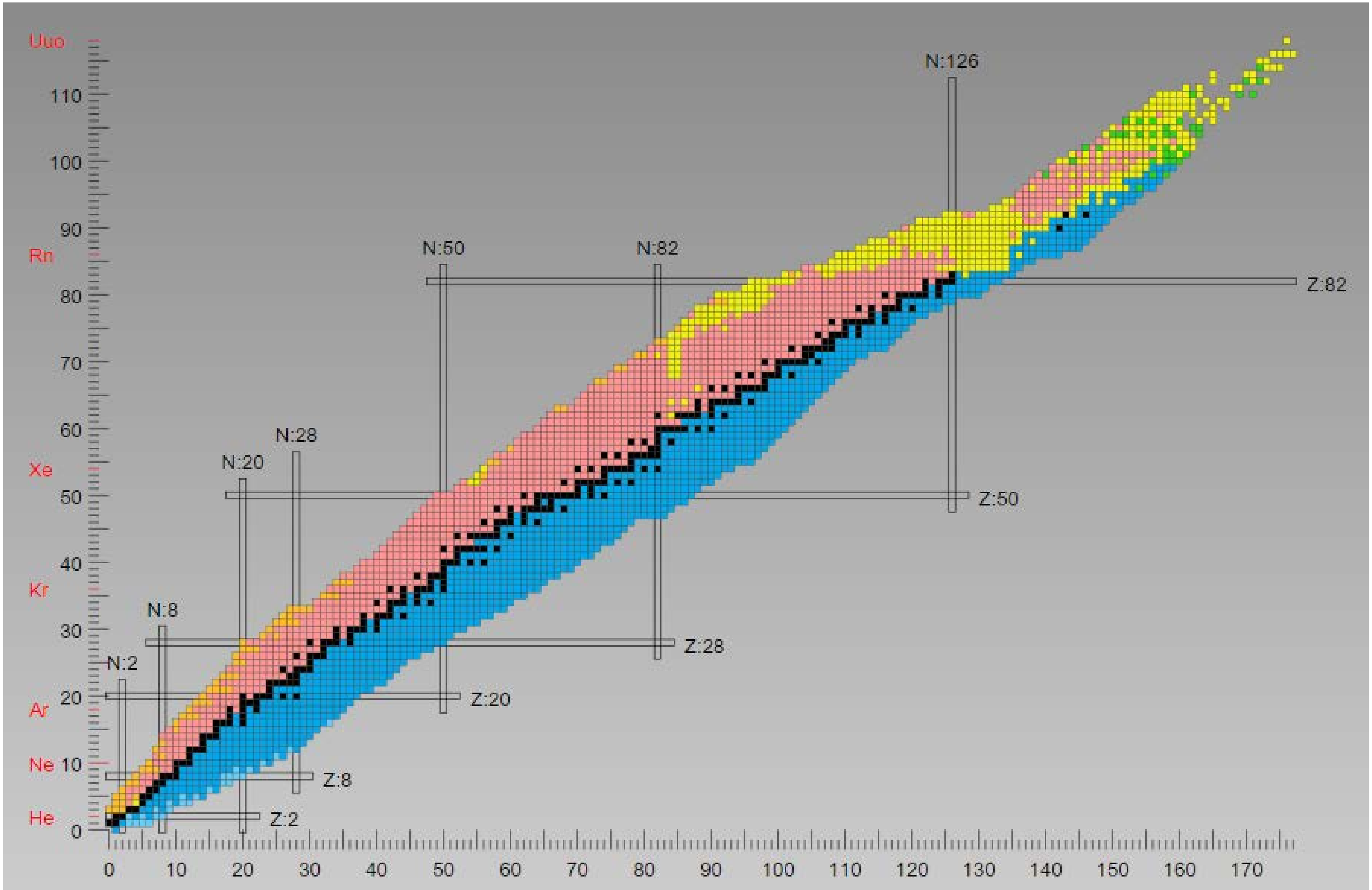
- To improve our knowledge of nuclear interaction
- To understand the reaction mechanisms
- To extract information about nuclear structure
- To learn about nuclear dynamics



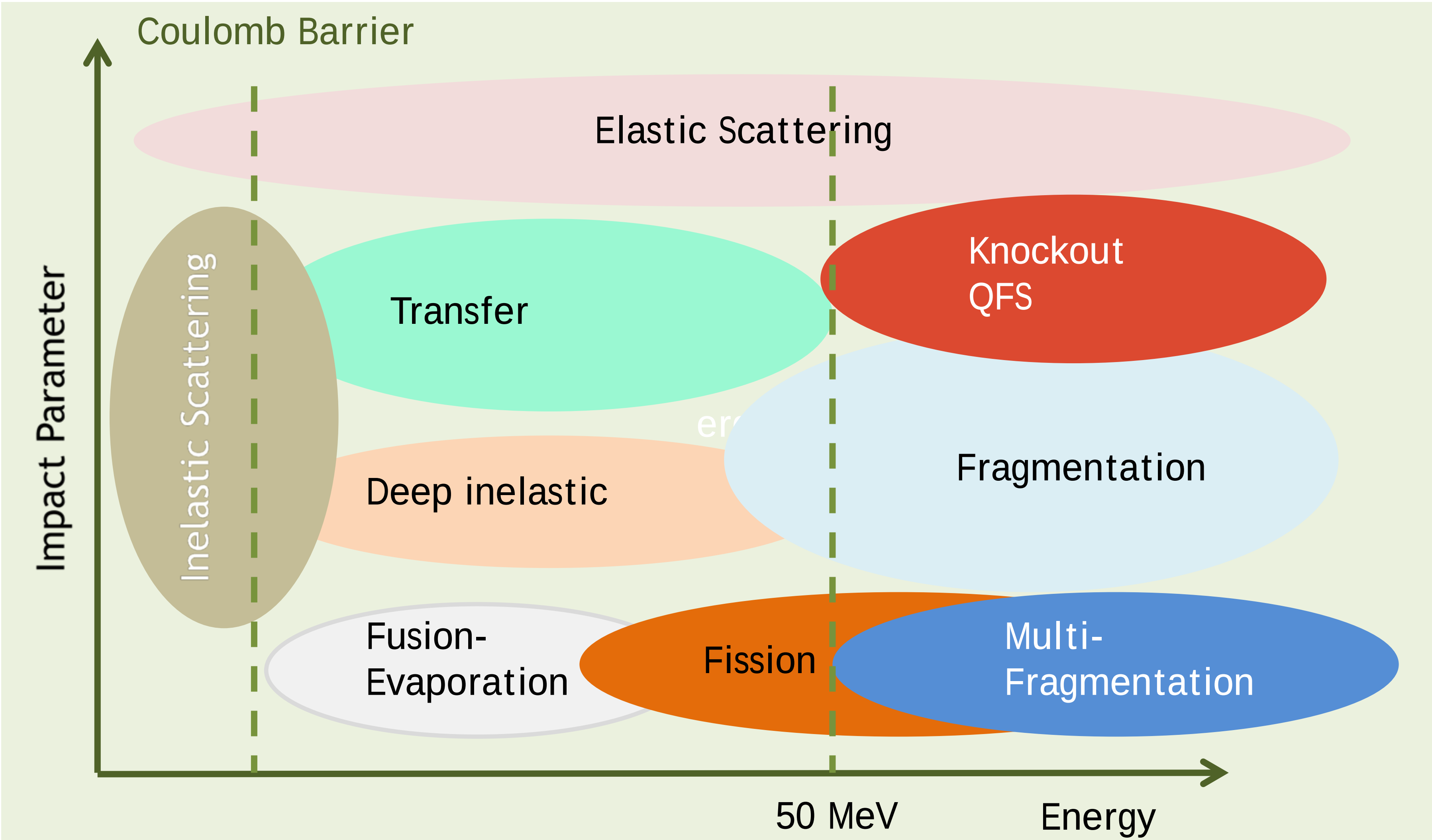


Nuclear reactions are behind phenomena studyed in our labs but also in stellar environment , and many important applications

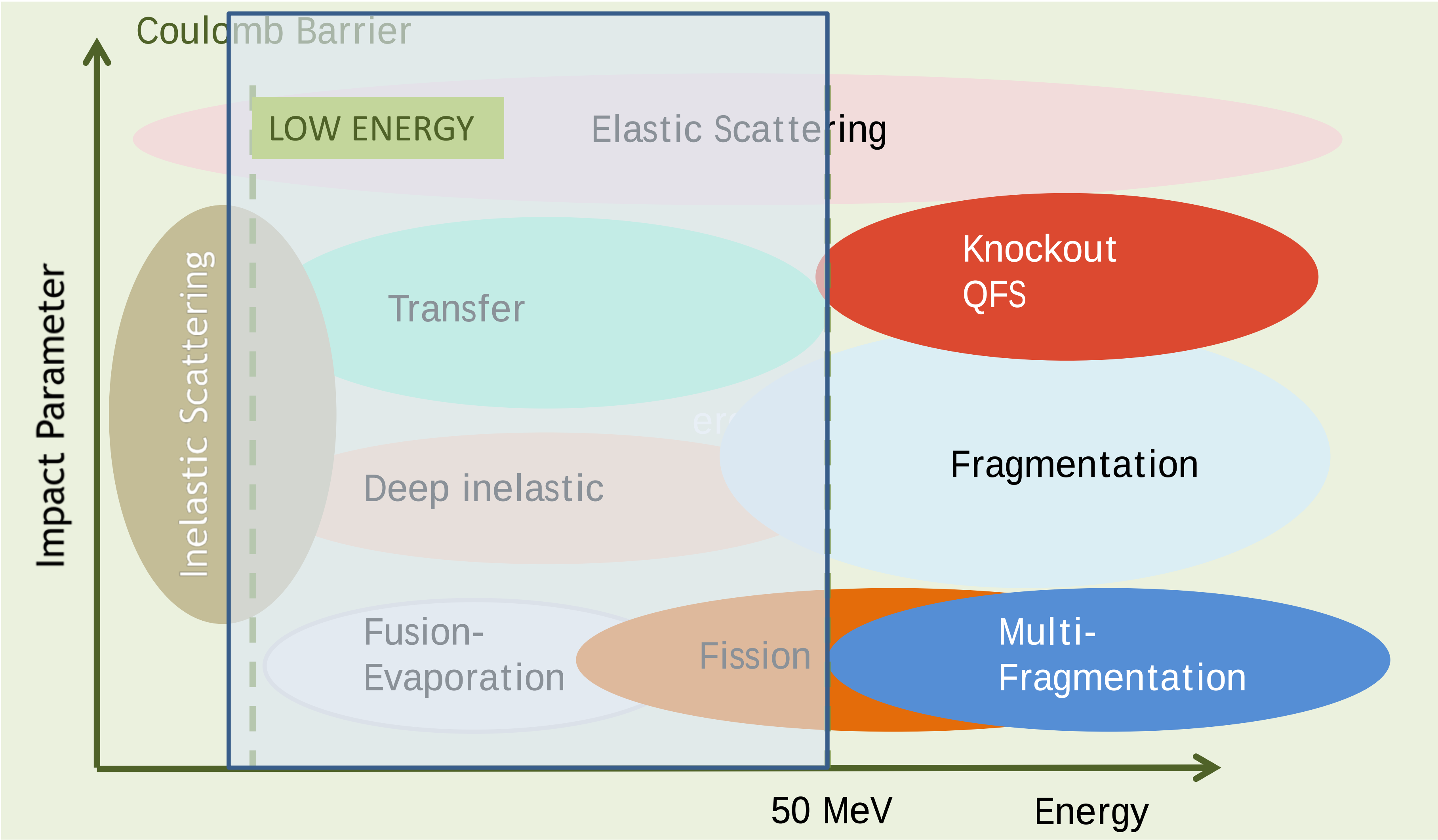
Today Nuclear Reactions



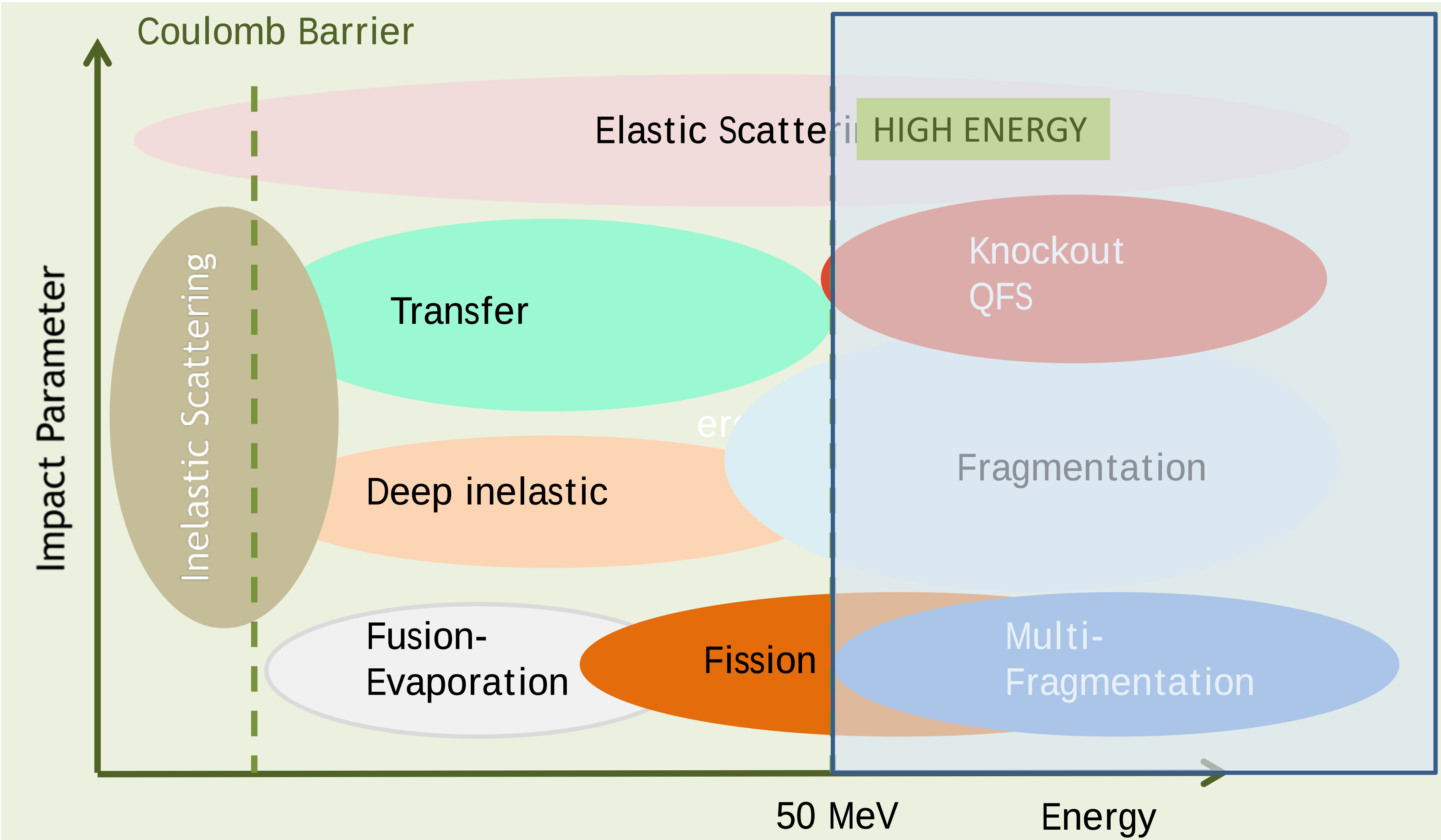
Nuclear Reactions Classification



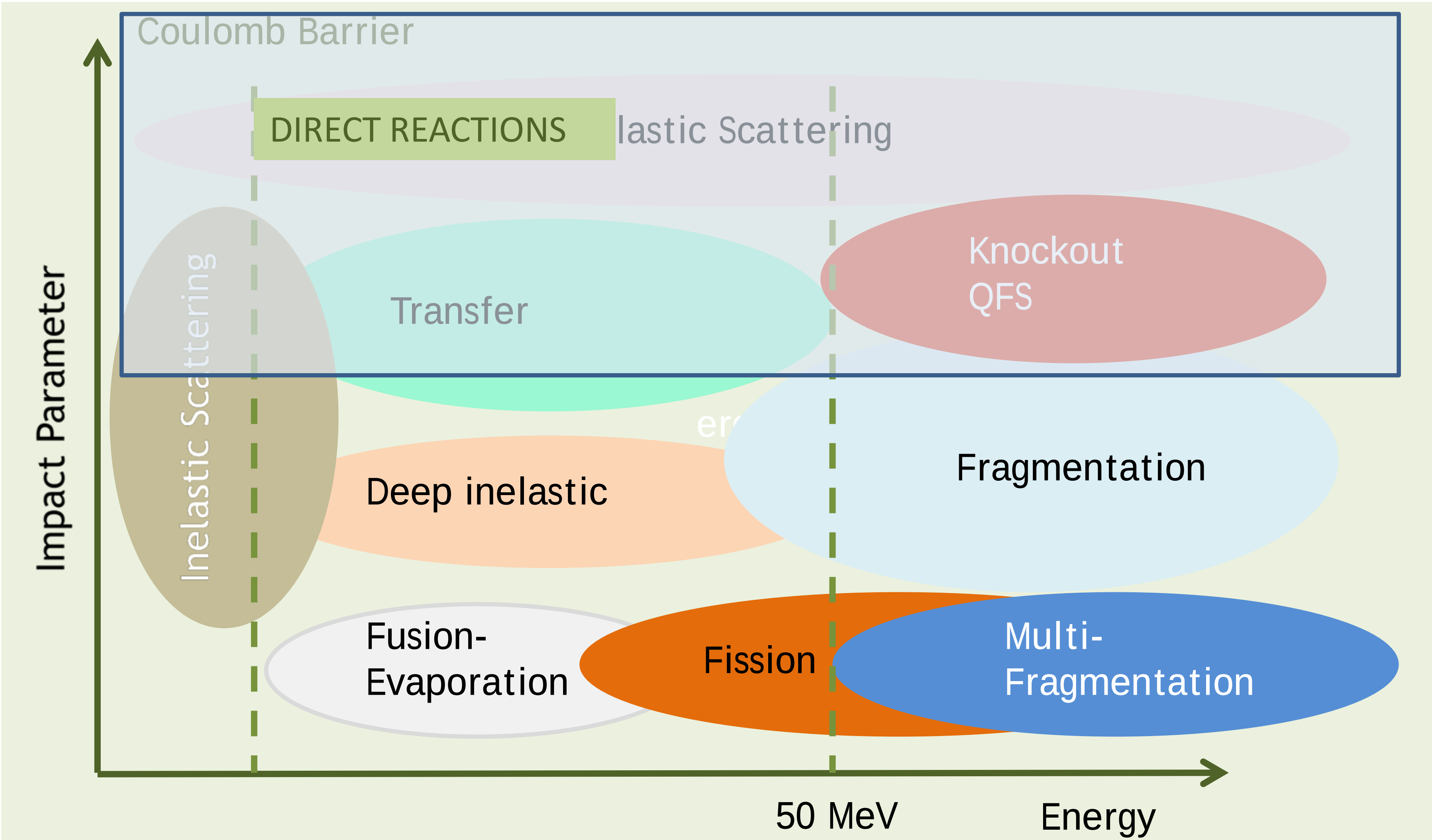
Nuclear Reactions Classification



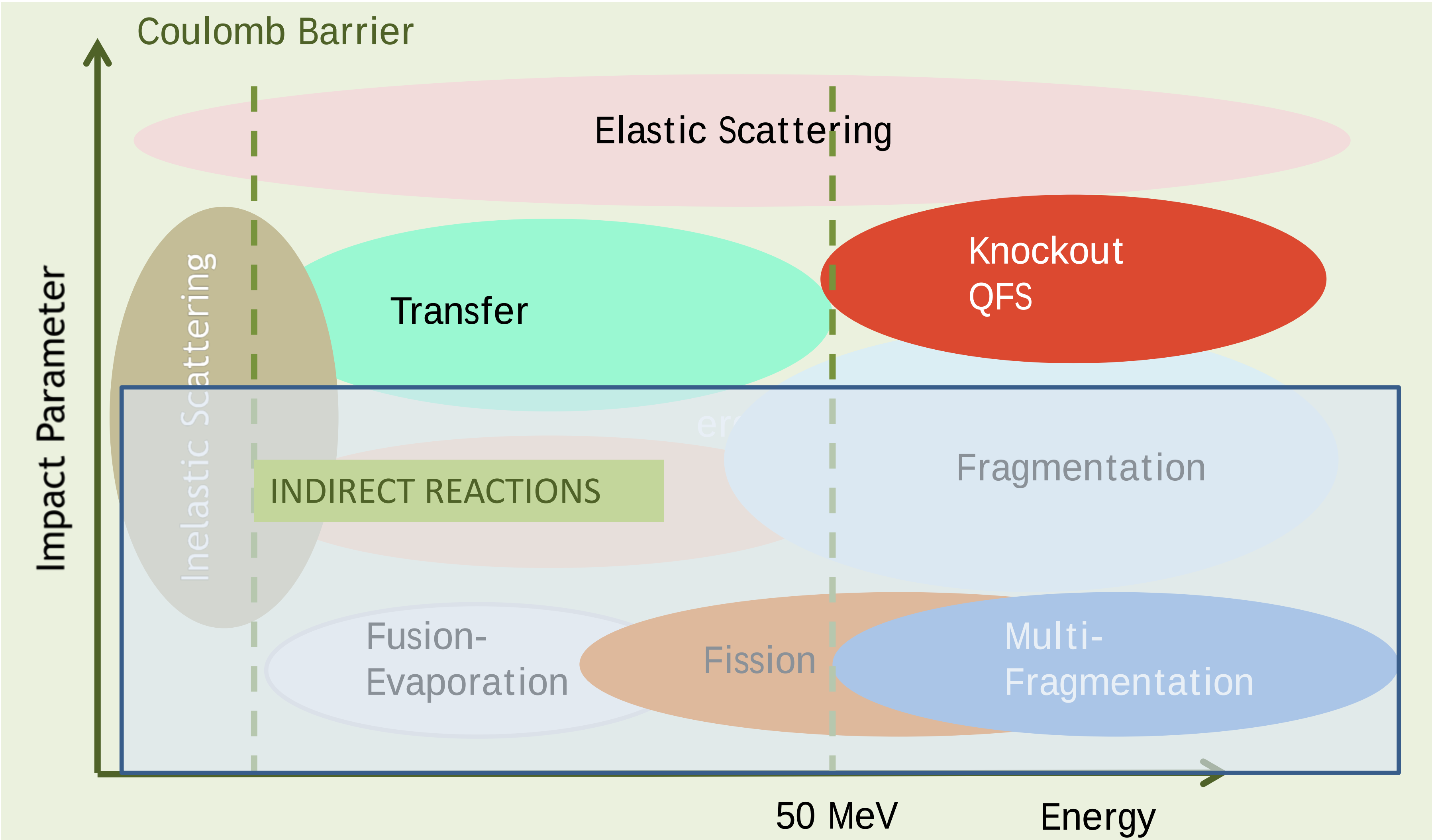
Nuclear Reactions Classification



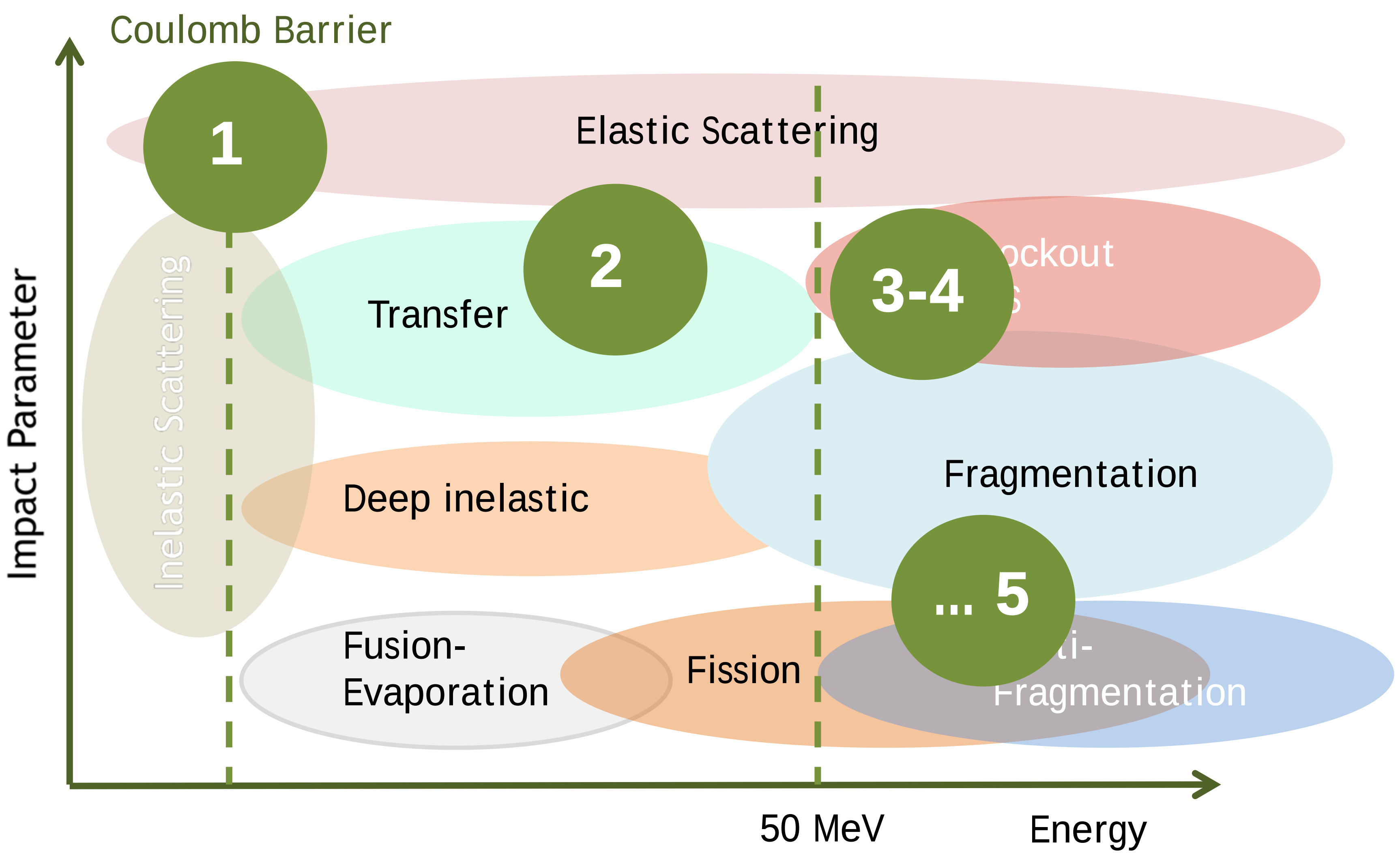
Nuclear Reactions Classification



Nuclear Reactions Classification



Nuclear Reactions Classification



Which are the experimental dreams?

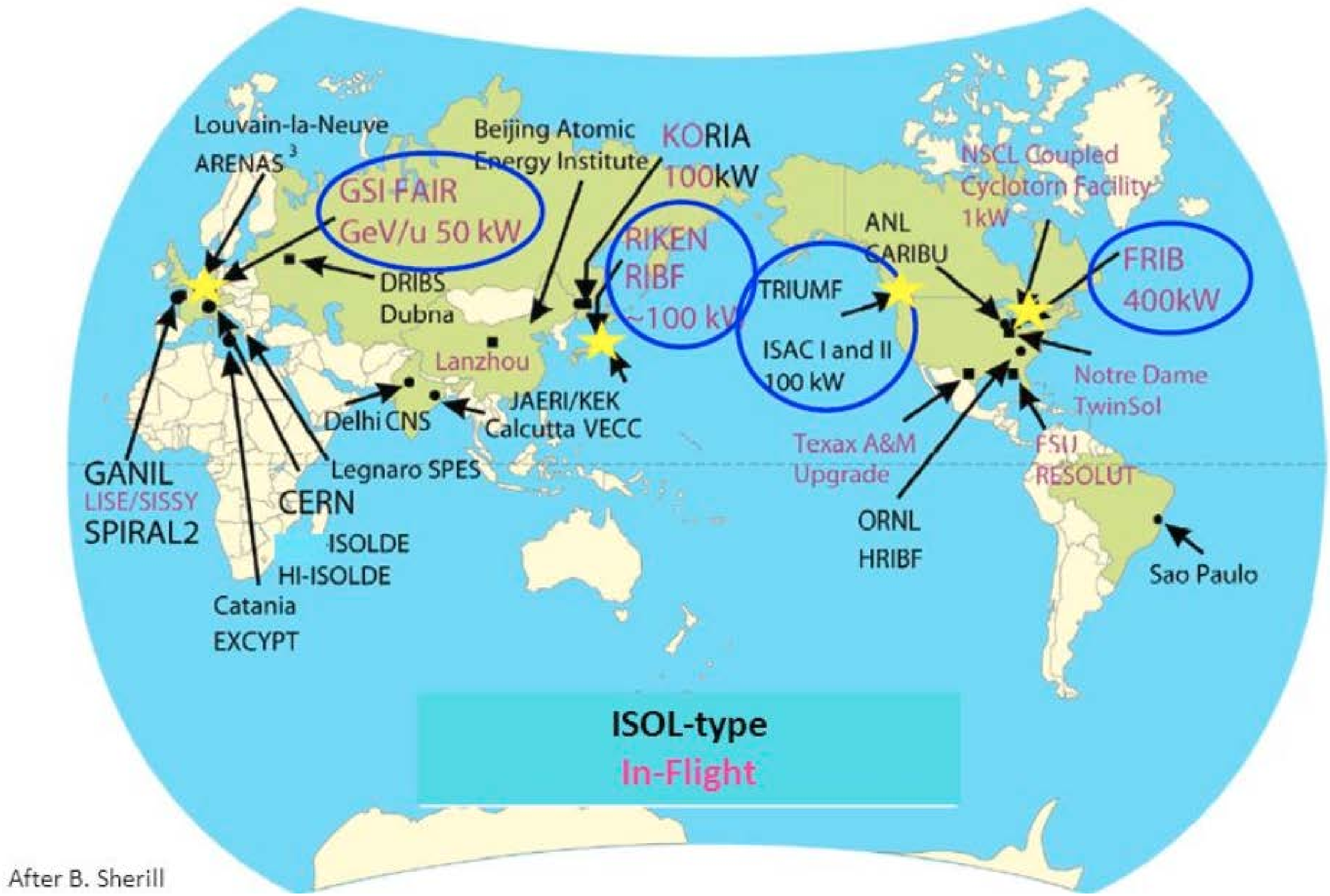
- High intensity: The highest possible production of the desired secondary beam
    - Different production mechanisms and **energy regimes**

- **High purity secondary beam: A secondary with excellent quality**
    - **Purification technique**
    - PID and eventually tracking

- Detection of the reaction products
    - High aceptance or large angular coverage: Complete detection of all reaction products,
    - Determination of particles of different nature
    - High granularity : Good energy and position resolution
    - High detection efficiency

The best experimental setup we could ever imagine would need of the join work of experimentalists and theoretitians

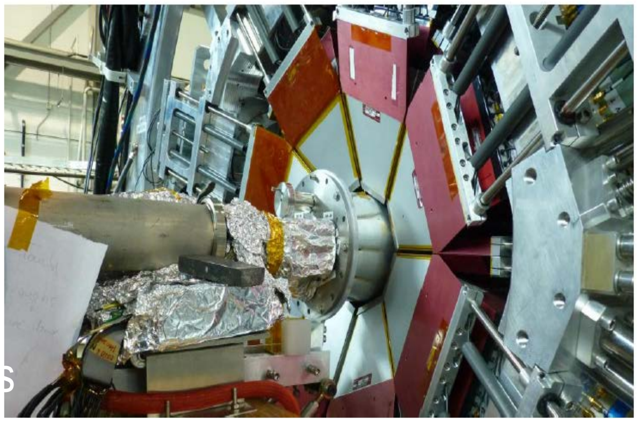
Existing and planned RIB facilities

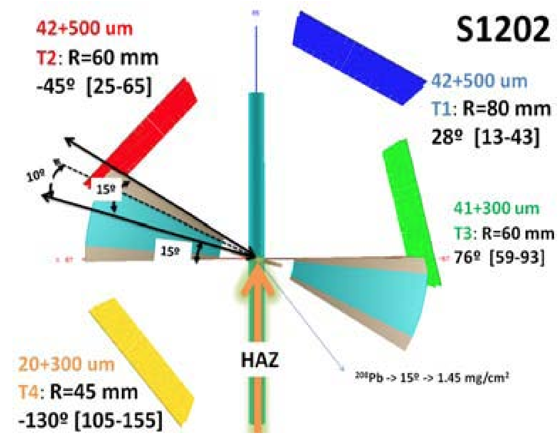


V. Pesudo et al Phys. Rev. Lett. 118 152502

Experiment @ Triumph

^{11}Be @ 2.9 and 3.6 MeV/u 10^5 $^{11}Be/s$

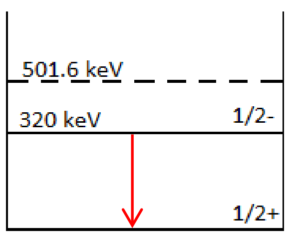




- 4 telescopes DSSSD for charge particle detection
- 8 Clover (TIGRESS) for g detection

This work allowed the **simultaneous detection of the elastic, inelastic and breakup channels**

Many available information on ^{11}Be



^{11}Be

Which is the mechanism responsible of the ^{11}Be scattering?

What can we learn of the ^{11}Be structure?

Scattering of the Halo Nucleus ^{11}Be on ^{197}Au at energies around the Coulomb Barrier

Optical Model:

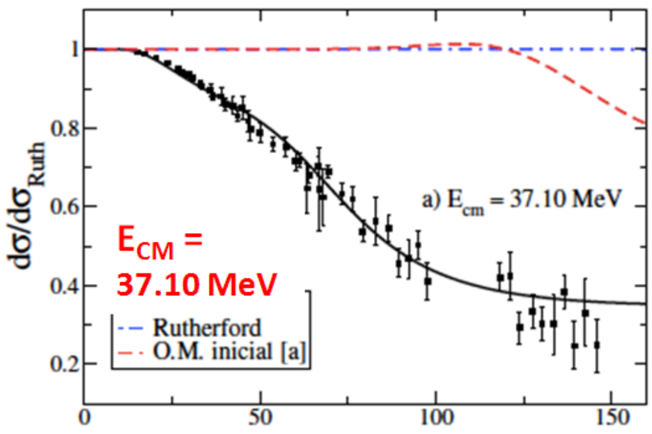
Effective potential determined

strong reduction with respect to Rutherford

- Large diffuseness → The halo structure of the ^{11}Be → Imaginary part (x10) to match the data.
- Large sensitivity radius 35-40 fm → indication of the importance of long range couplings

Only collective properties of the nuclei can be extracted using this formalisms.

^{11}Be + ^{197}Au elastic scattering



Semiclassical Calculations:

Include Coulomb coupling at first order. Pure Coulomb trajectories an E1 excitation of the ^{11}Be projectile due to Coulomb interaction with target.

Continuum Discretised Coupled Channel (CDCC):

Full quantum description of the $^{11}Be+^{197}Au$ reaction, starting from a two-body structure model for the halo-nucleus

Ingredients are model space and interaction potential

$$V[n-^{10}Be] \quad + \quad V[n-^{197}Au] \quad + \quad V[^{10}Be + ^{197}Au]$$

Structure of ^{11}Be
P. Capel et al, PRC70 (2004) 064605

Koning & Delaroche
NPA713 (2003) 231

From ^{10}Be + ^{208}Pb data
Kolata et al., PRC69(2007)047601

Continuum Discretised Coupled Channel (CDCC) + Structure Model of ^{11}Be: XCDCC

Includes a non-spherical ^{10}Be with deformation reproducing the B(E2) value (extension of CDCC including internal degrees of freedom of the participants)

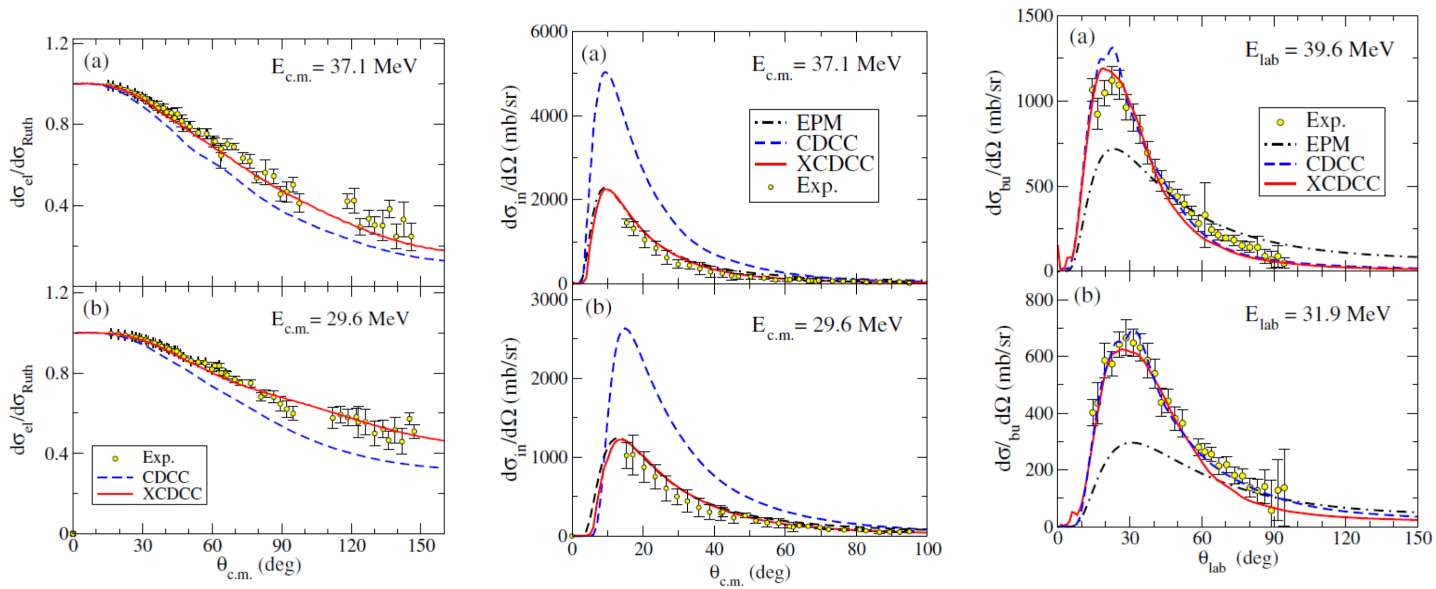
Scattering of the Halo Nucleus ^{11}Be on ^{197}Au at energies around the Coulomb Barrier

XCDCC + full ^{11}Be structure

$$|^{11}Be(gs)\rangle = \alpha|^{10}Be(gs)\quad 2s_{1/2}\rangle + b|^{10}Be(2^+)\quad 1d_{5/2}\rangle + \gamma|^{10}Be(2^+)\quad 1d_{3/2}\rangle$$

Excited states of ^{11}Be in the continuum with $J^p = ½^{\pm}, 3/2^{\pm}, 5/2^{\pm}........ 15/2^{\pm}$

Excitation energy up to 14 MeV



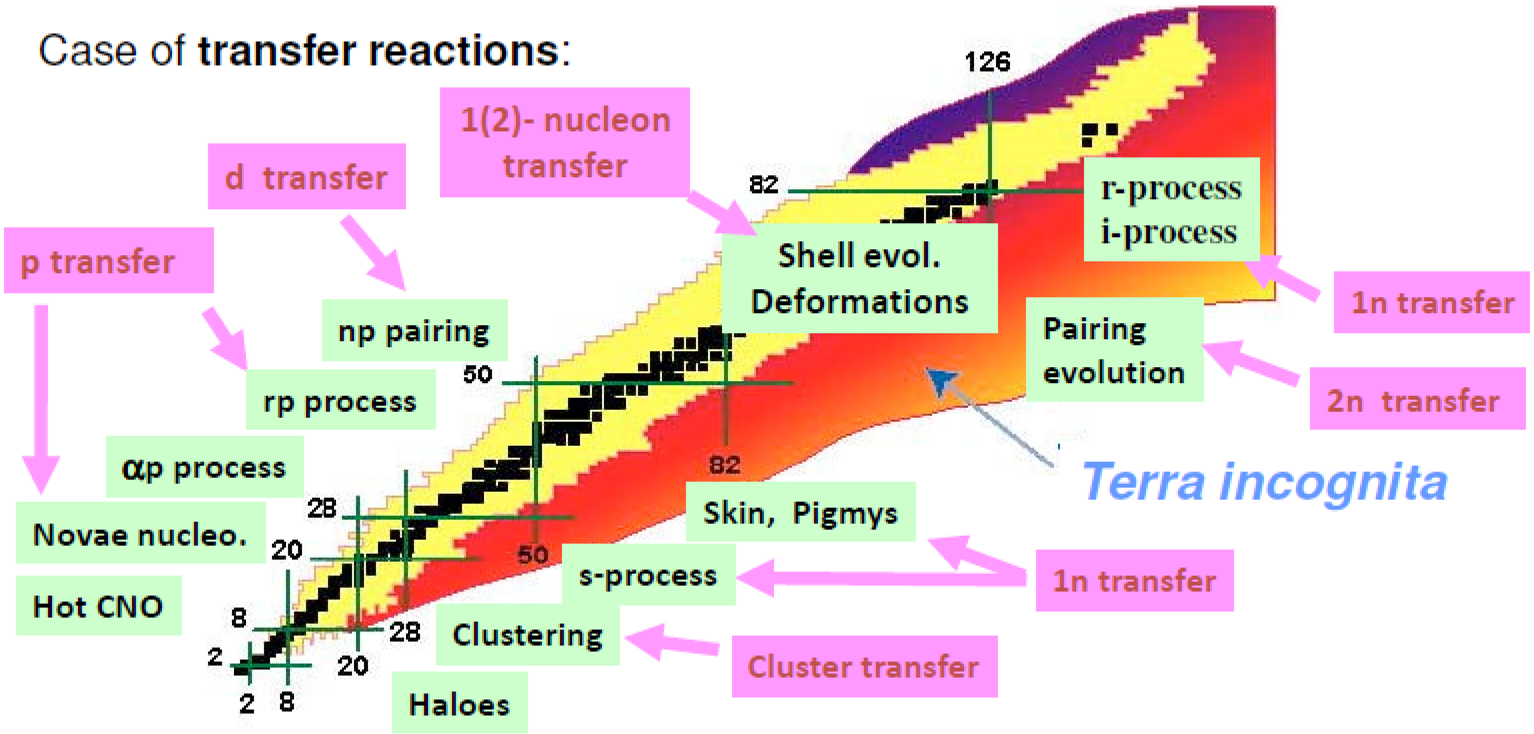
- The XCDCC calculation is able to reproduce the elastic, inelastic and breakup channels

- The simplistic approach of ^{10}Be(gs) +n + ^{197}Au is not able to describe the differential cross sections → Adequate tools to analyze low energy Coulomb breakup reactions

Transfer reactions (at low and intermediate energies)

A great tool to investigate Exotic Nuclei and Astrophysical processes

Case of **transfer reactions**:



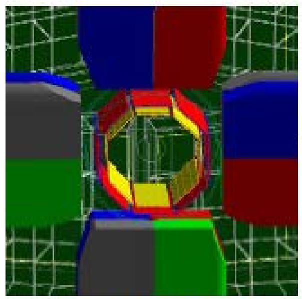
Good energy regime : 5 ~ 50 MeV/u → **Core program for ISOL facilities**

Source: D. Beaumel

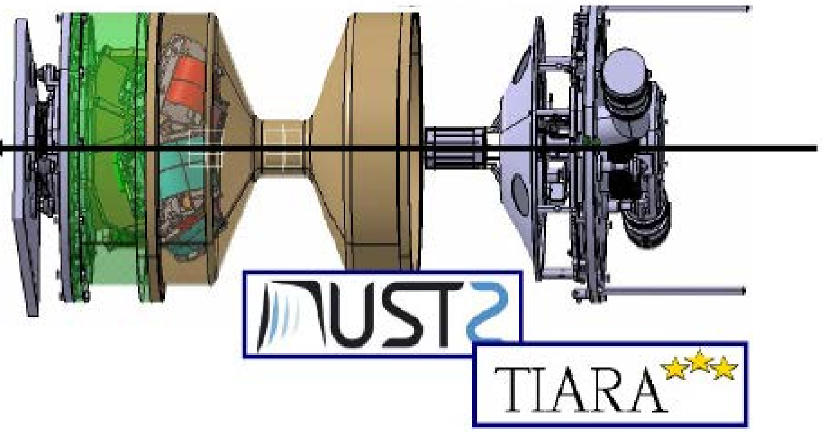
Transfer reactions (at low and intermediate energies)

Si-based systems currently operating for p-γ coincidence measurements

γ-rays $\Rightarrow E_x$

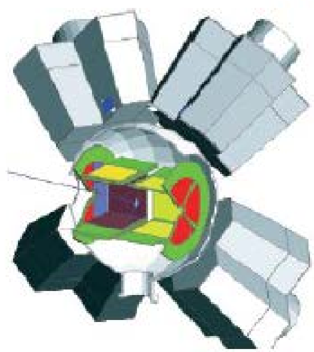


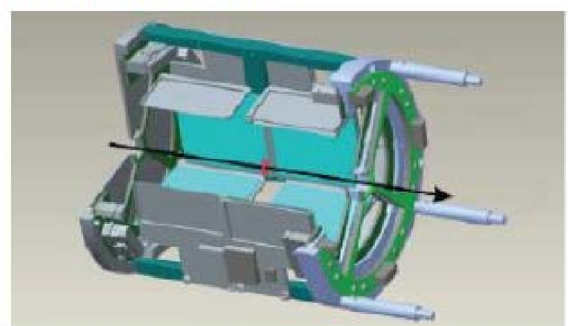
4 EXOGAM



Complementary γ detection

T-REX + MINIBALL





Source: D. Beaumel

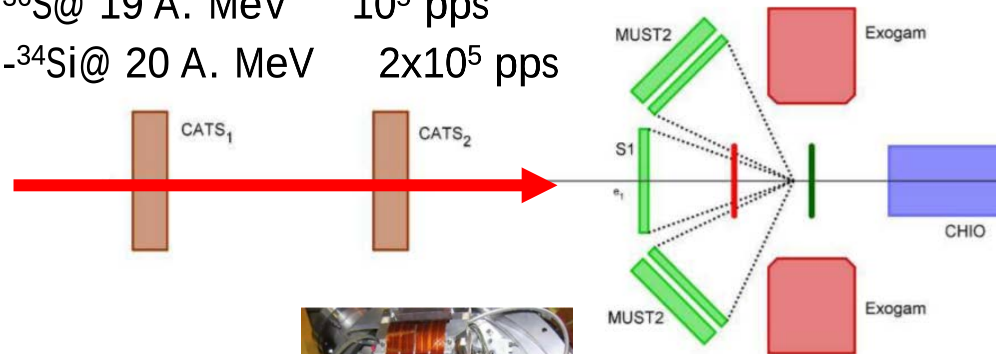
Burgunder et al., PRL112 042502 (2014)

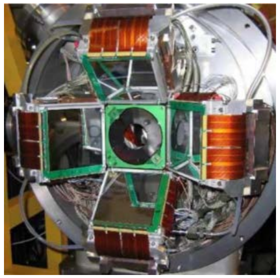
Detection of the light recoil particle (E and θ) + γ detection
Observables : differential cross-section , excitation energy , Information : spins, parities ...

Goal: Study the change in the neutron $2p_{3/2}$ -2 $p_{1/2}$ SO splittings between the ^{37}S and ^{35}Si nuclei caused by the filling of the proton $2s_{1/2}$ orbit, using (d, p) transfer reactions in inverse kinematics

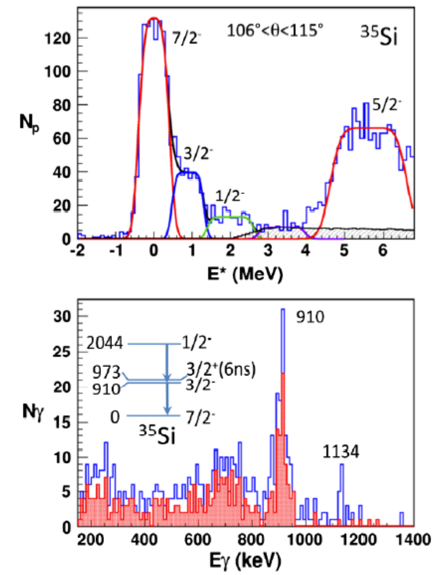
Experiment @ GANIL

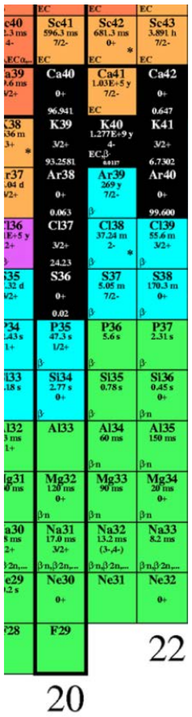
^{36}S@ 19 A. MeV 10^5 pps
-^{34}Si@ 20 A. MeV 2×10^5 pps



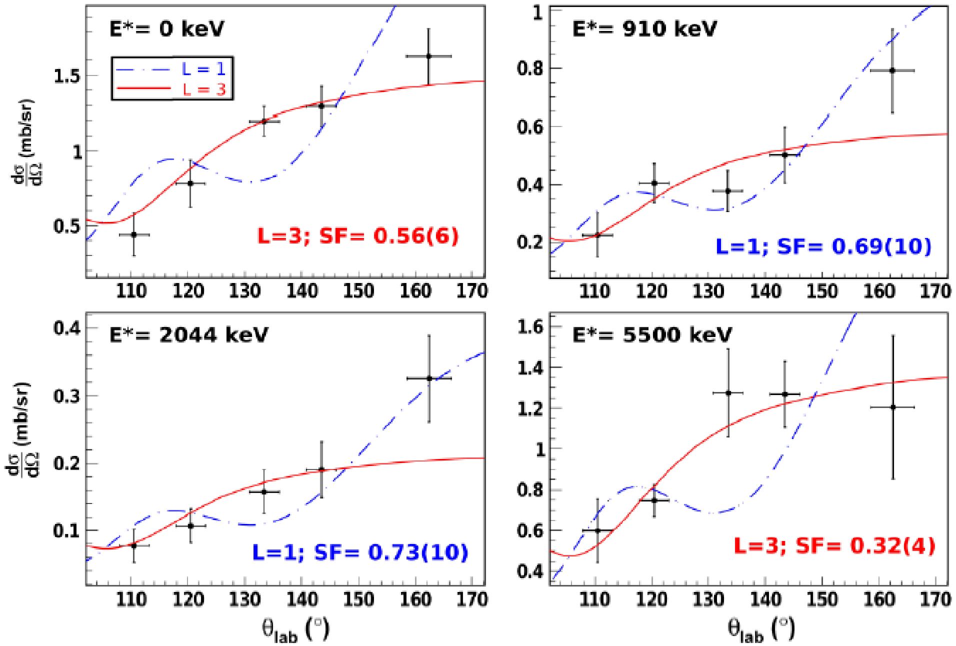


^{34}Si(d,p)^{35}Si





$^{34}Si(d,p)^{35}Si$

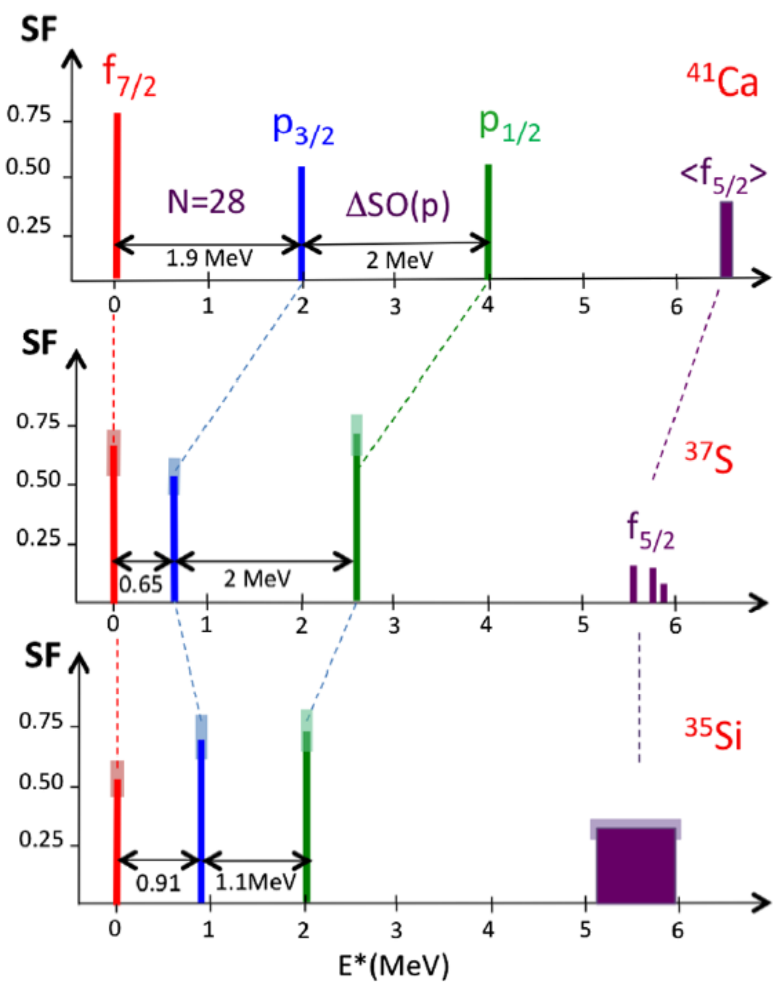


- Experimental angular distributions for the ^{35}Si states identified
- The curves correspond to ADWA calculations assuming transfer to l=1

(dashed-dotted line) or l =3 (solid line) states. → The shape and absolute and absolute xsec allows the assignment of spin and SF

- ADWA calculations take into account deuteron breakup to all orders .
- SF are quenched
- Target excitations are not included

Experimental Study of the Two-Body Spin-Orbit Force in Nuclei



The p SO spliting was determined experimentally and evaluated with Shell Model calculations → in which the monopole terms are forced to match the experimental energies

$$\Delta SO(p) \simeq \Delta 2s_{1/2}(V^{pn}_{2s_{1/2}2p_{1/2}} - V^{pn}_{2s_{1/2}2p_{3/2}})$$

- The derived strength of the two-body SO interaction is well reproduced by realistic NN forces such as **N3LO and KLS → predictive power ?**
- After quenching the Shell Model SF´s agree with the experimental values

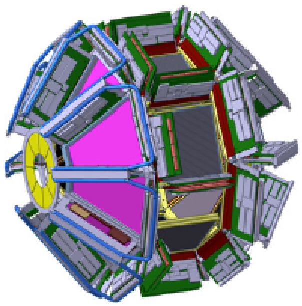
Transfer reactions (at low and intermediate energies)

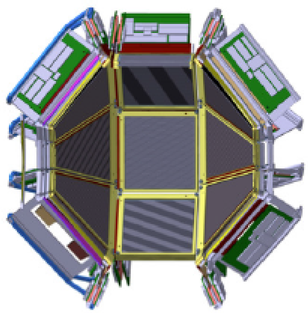
GRIT project

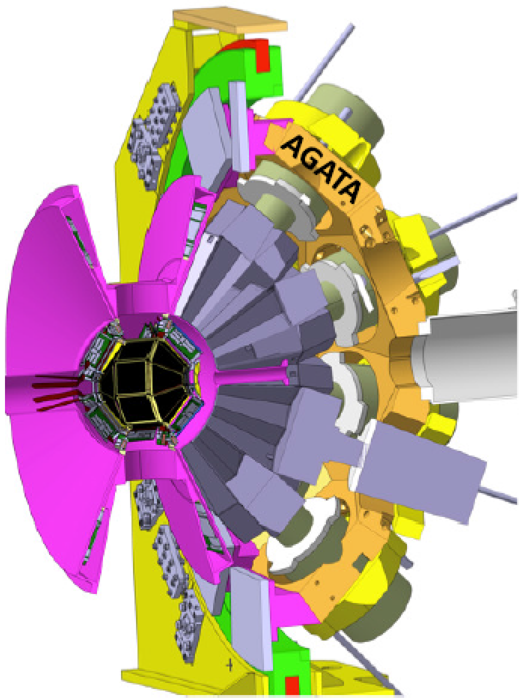
(Granularity, Resolution, identification, Transparency)

(GASPARD-TRACE collaboration)

4π Si array fully integrable in AGATA & PARIS







- High efficiency for particles and gamma-rays
- High granularity (strip pitch < 1 mm)
- Large dynamical range
  0.5 + 1.5 + 1.5 mm thick DSSD's (forward hemisphere)
  0.5 + 1.5 mm DSSD's (backward hemisphere)
- Special targets (Cooled ^{3,4}He cell, pure H, tritium)
- PID using Pulse Shape Analysis techniques
- New Integrated electronics

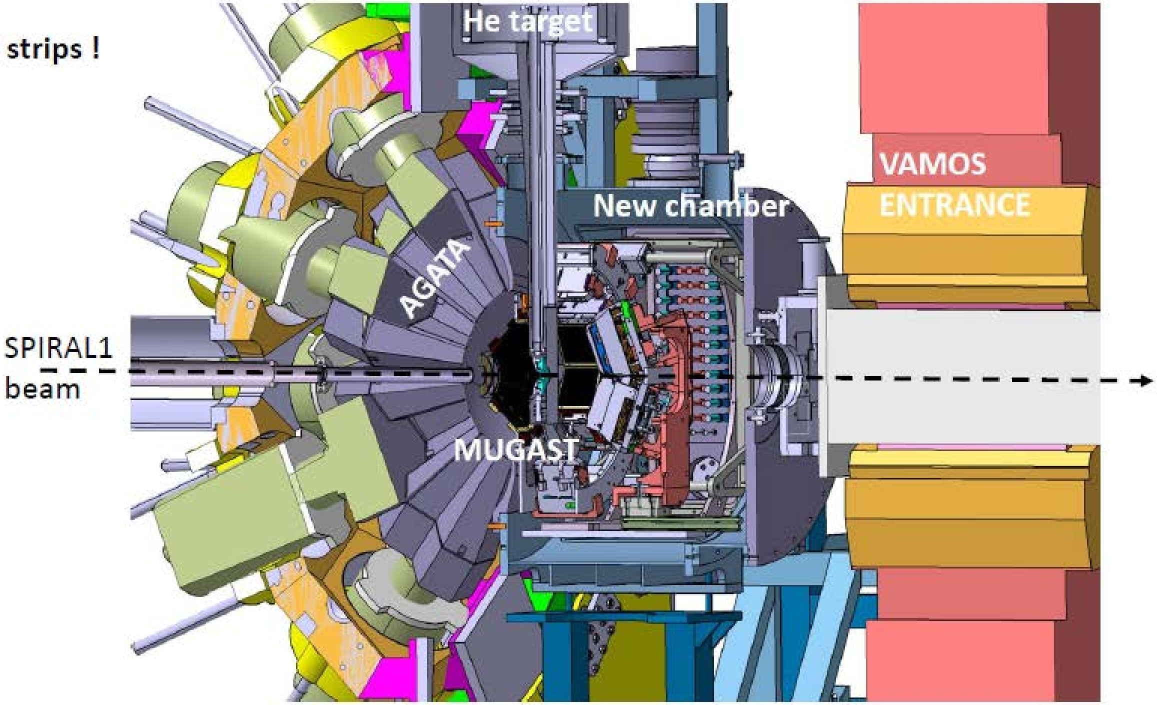
Source: D. Beaumel

Transfer reactions (at low and intermediate energies)

MUGAST ***an intermediate step towards the ultimate array***

MUGAST: New detectors of GRIT + MUST2 electronics coupled with AGATA @ VAMOS
⇒ First High resolution Direct Reactions studies at Ganil (new SPIRAL1 beams)

3000 strips !



First campaign with Spiral1 beams foreseen 2019-2020

IPNO, INFN-Padova, Surrey, Santiago, GANIL

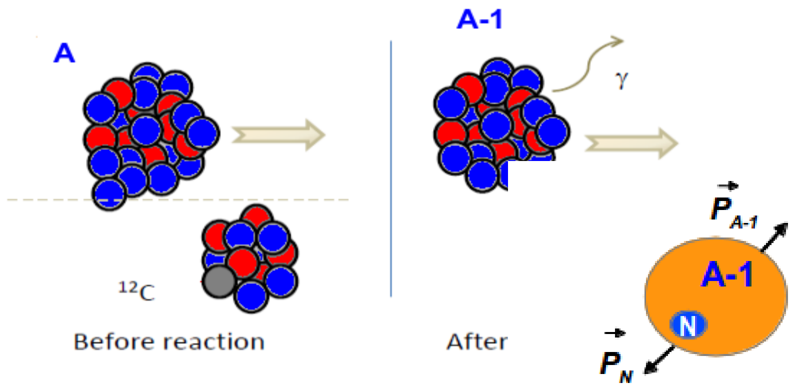
2018 →
3 experiments
with MUST2

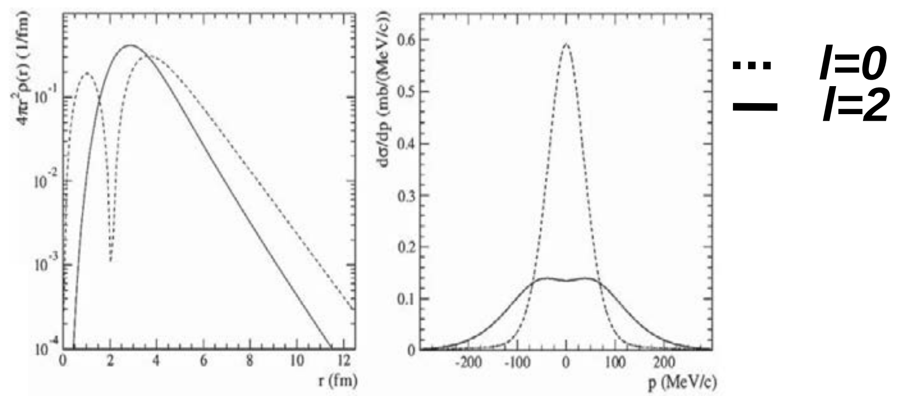
2019-2020 →
MUGAST

Source: D. Beaumel

One nucleon knock-out

Exotic projectiles at high energy



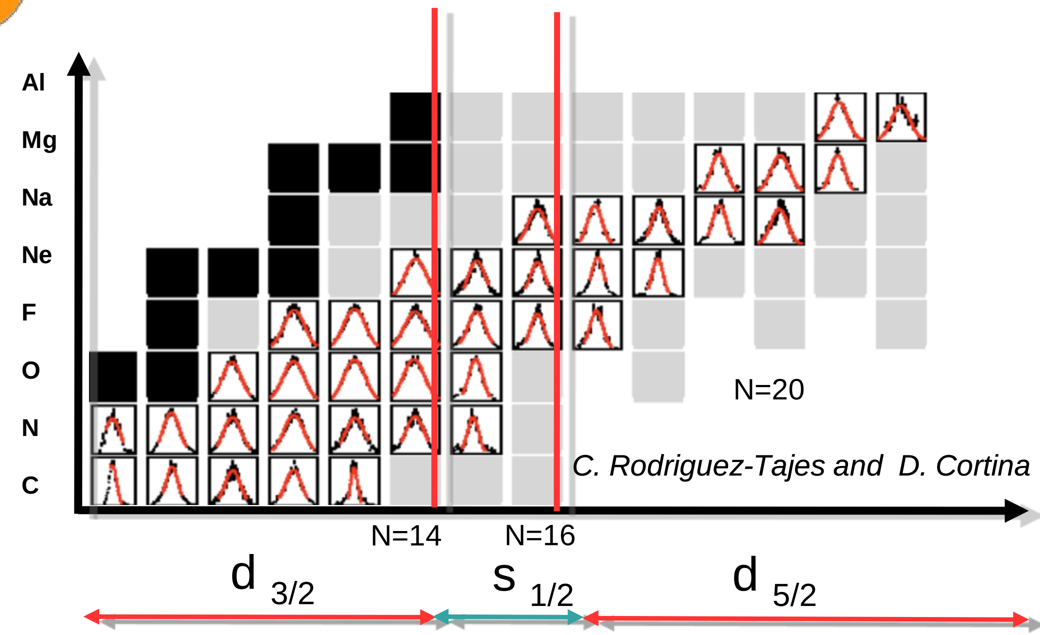


Detection of the heavy recoil + γ detection

Observables : cross-section , momentum distributions energy

Information : SF spins, parities …

- Explore the external part of the wave function
- sensitivity to *l*
- Evolution of the nuclear structure



$$| P > = \sum C^2S \left(| C > \otimes | n> \right)$$

removed neutron

~ Spectroscopic factor

^{A-1}X fragment

Cross-sections

Gamma ray tagging

^{A-1}X fragment momentum distribution

Experiment @NSCL.
RIKEN, GSI, Lanzhou

Determination of experimental Reduction factors

$$R_s = \sigma_{exp}(I^{\Pi}) / \sigma_{theo}(I^{\Pi})$$

Interplay between reaction model and nuclear structure

$$\sigma_{theo}(I^{\Pi}) = \sum_j C^2S_j (I^{\Pi}, nlj)\, \sigma_{sp}(S_n, nlj)$$

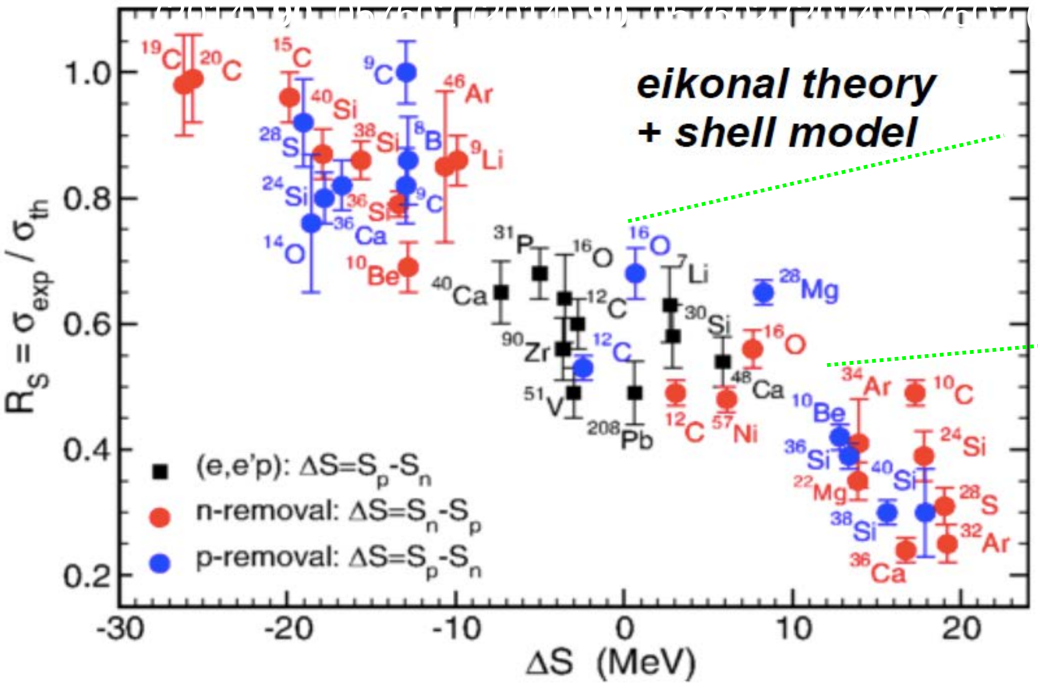
SP spectroscopic Factors from Shell model

SP cross section from Eikonal theory

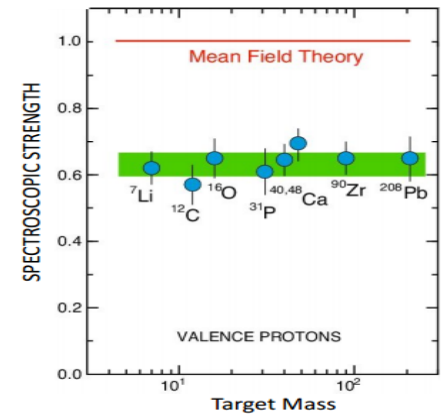
Systematics of intermediate-energy single nucleon removal cross section

A. Gade et al., Phys. Rev C 77, 044306 (2008)

B. J. Tostevin and A. Gade, Phys. Rev C 90 057602 (2014)



I. Sick, Progress in Particle and Nuclear Physics 59, 447 (2007)

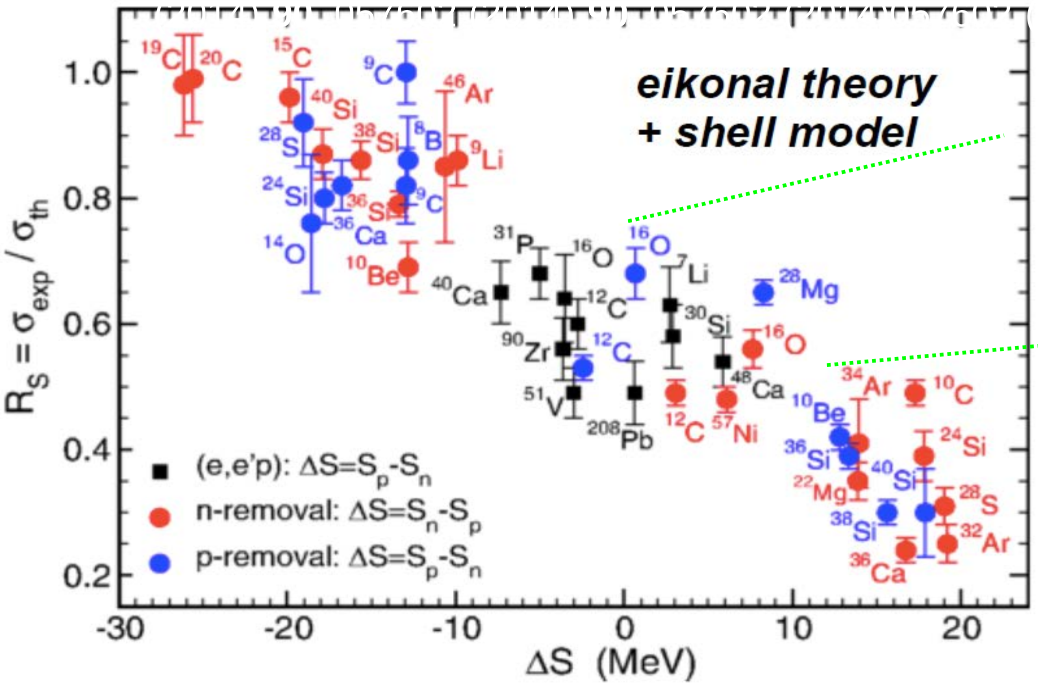


Enhancement of correlations in asymmetric nuclear matter
(strongly bound valence nucleon)

Systematics of intermediate-energy single nucleon removal cross section

A. Gade et al., Phys. Rev C 77, 044306 (2008)

B. J. Tostevin and A. Gade, Phys. Rev C 90 057602 (2014)



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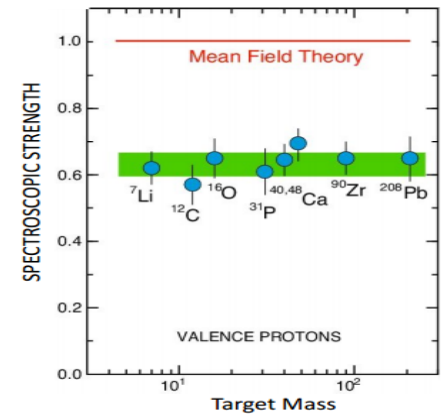

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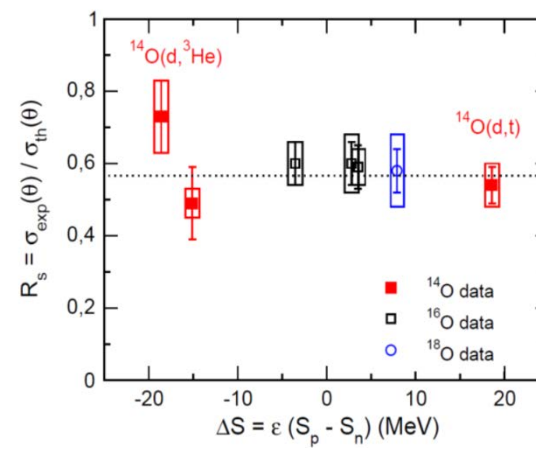
Comparison with transfer reactions

F. Flavigny et al., Phys. Rev. Lett. 110, 122503 (2013)

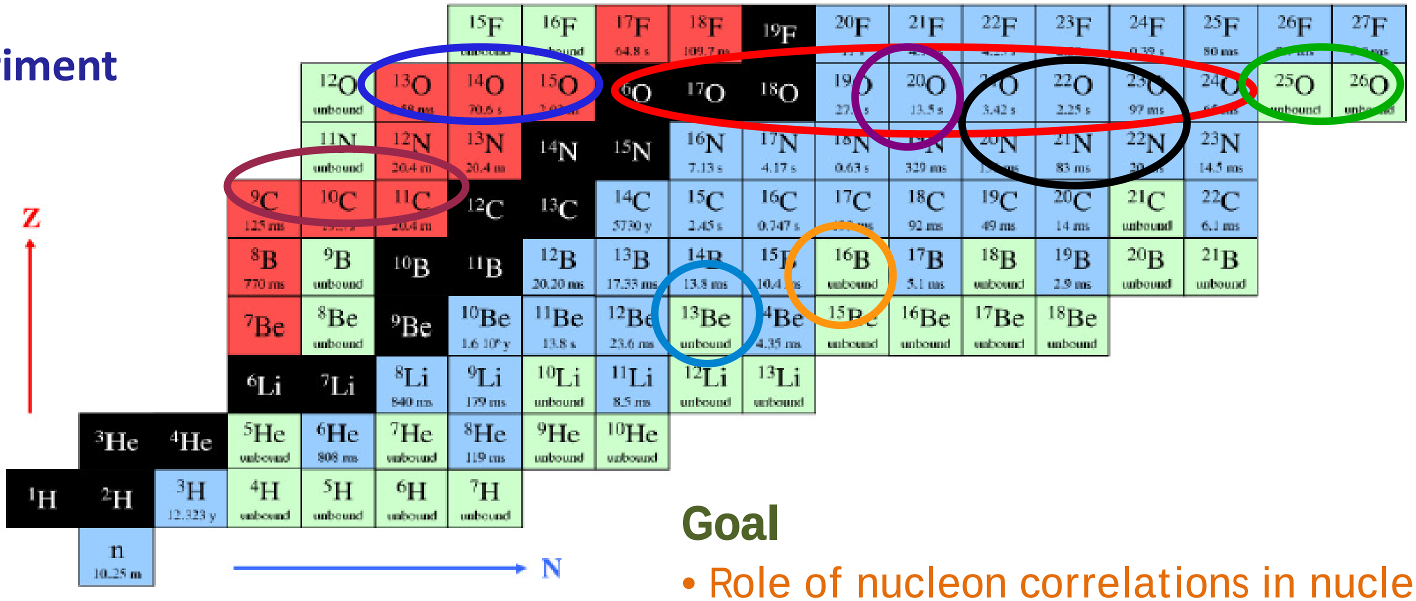


^{40}Ar primary beam @ 490 A MeV
Exotic projectiles raning from Z=4 to Z=8 spaning over N/Z
Different reaction targets Pb, C, CH_2
→ (p,2p) reactions induced by exotic projectliles

Experiment @ GSI

S393 experiment

L. Atar
P. Díaz
JM. Boillos
C. Caesar
M. Holl
N. Al Nafaj
G. Ribero
R. Thies



Goal

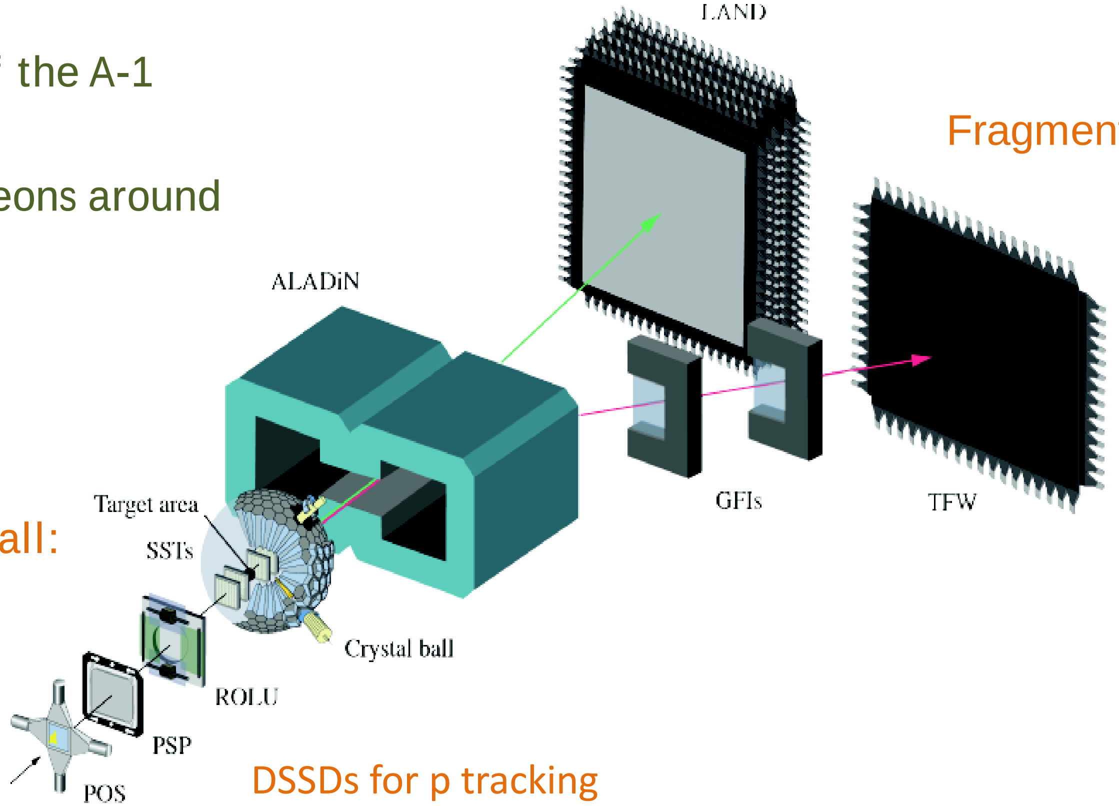
- Role of nucleon correlations in nuclei
- Detailed spectroscopy, deeply bound states
- Study of unbound states beyond the dripline
→ invariant mass method

Exclusive measurements of quasi-free proton scattering reactions in inverse and complete kinematics

- Measuring the momentum of the recoil N and the g de-excitation
- Measuring the de-excitation of the A-1 fragment and its momentum
- Measuring the correlated nucleons around the target
- Measuring n at 0 degree

Neutron arm

Fragment arm



Crystal Ball:

Secondary beam @

400 A Mev

CH_2,

DSSDs for p tracking

Reaction Theory different approaches

- **Quasifree (*p*,2 *p*) and (*p*, *pn*) reactions with unstable nuclei**

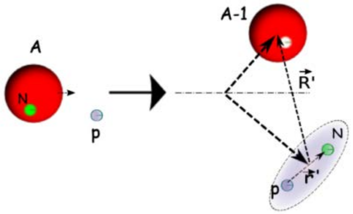
T. Aumann,C. A. Bertulani, and J. Ryckebusch
PHYSICAL REVIEW C **88**, 064610 (2013)

Based DWIA method and the use of eikonal scattering waves to include absorption from the elastic channel due to multiple-scattering effects.

- **Three-body model for the analysis of quasifree scattering reactions in inverse kinematics**

AM. Moro
PHYSICAL REVIEW C **92**, 044605 (2015)

Extension of the continuum-discretized coupled-channels (CDCC) method, using an expansion of the three-body final states in terms of eigenstates of the *p*-*N* Hamiltonian



- **Distortion effects on the neutron knockout from exotic nuclei in the collision with a proton target**

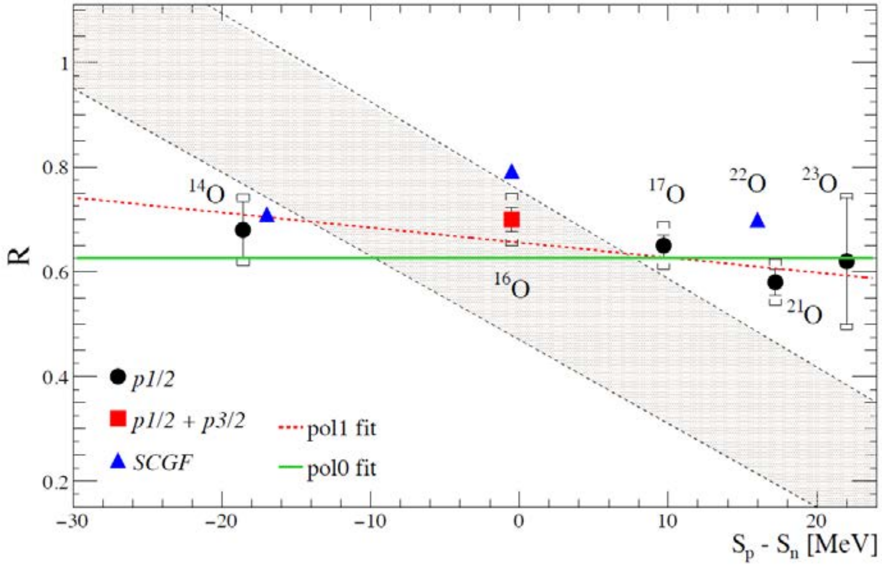
E. Cravo, R. Crespo and A. Deltuva
PHYSICAL REVIEW C 93, 054612 (2016)

Uses the three-body Faddeev/Alt-Grassberger-Sandhas (Faddeev/ AGS) framework . This reaction formalism exactly takes into account higher order re-scattering terms

Quasi-free (p,2p) reactions on oxygen isotopes: Observation of isospin independence of the reduced single-particle strengthns at low energy

L. Atar et al. Accepted in Phys. Rev. Lett. Nov 2017

Measurement of inclusive (p,2p) cross sections for oxygen isotopes using the quasi-free scattering technique in inverse kinematics and extracted the single-particle reduction factor R (Shell Model + Eikonal theory)

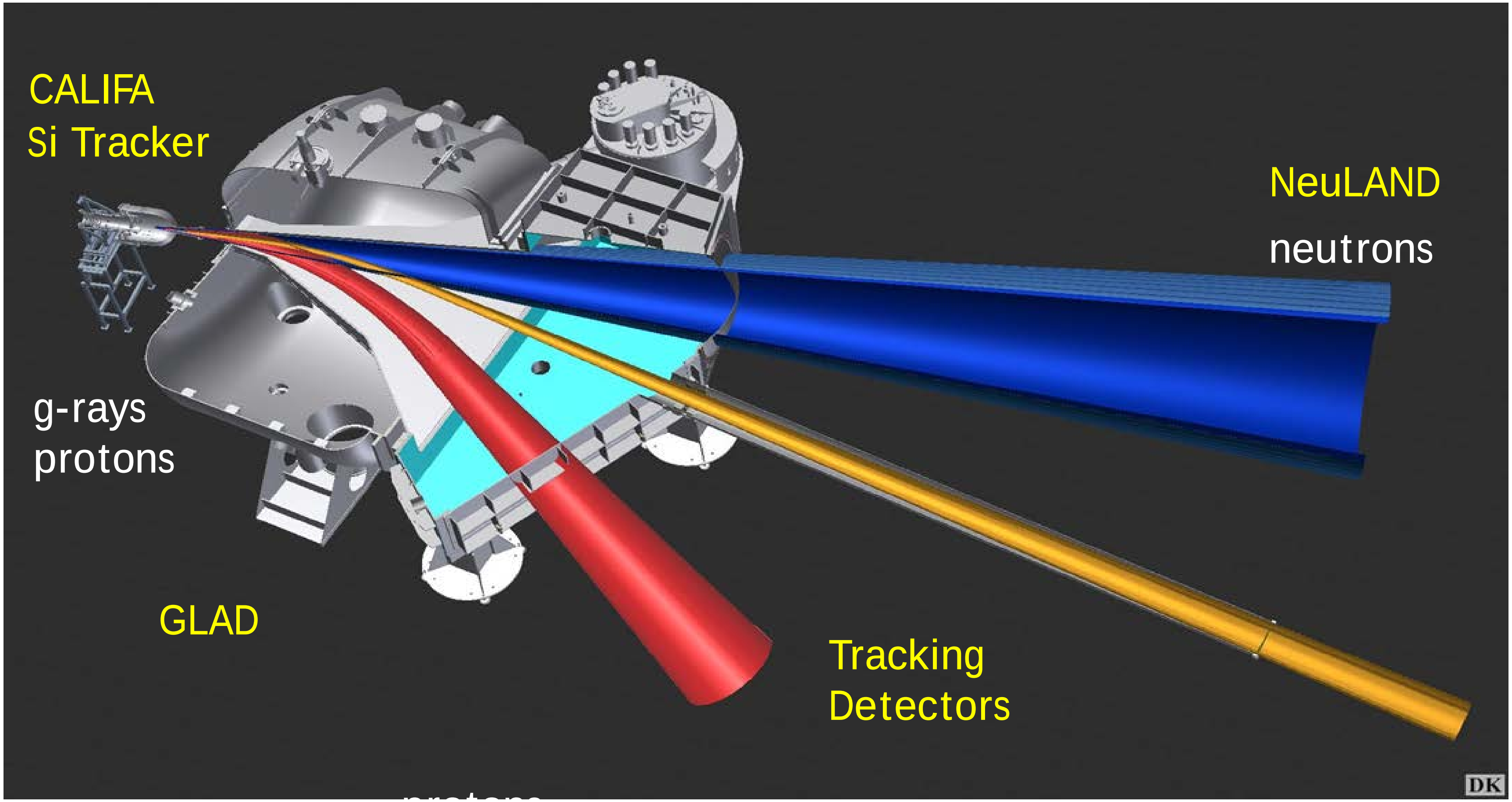


This dependence differs
Of the results obtained
In one-nucleon removal
Systematics

→ deficiencies of the eikonal theory at intermediate energies?

→ ??

Evaluation of SF with state of art ab-initio calculations as self-consistent Green's function are in agreement with the experimental results



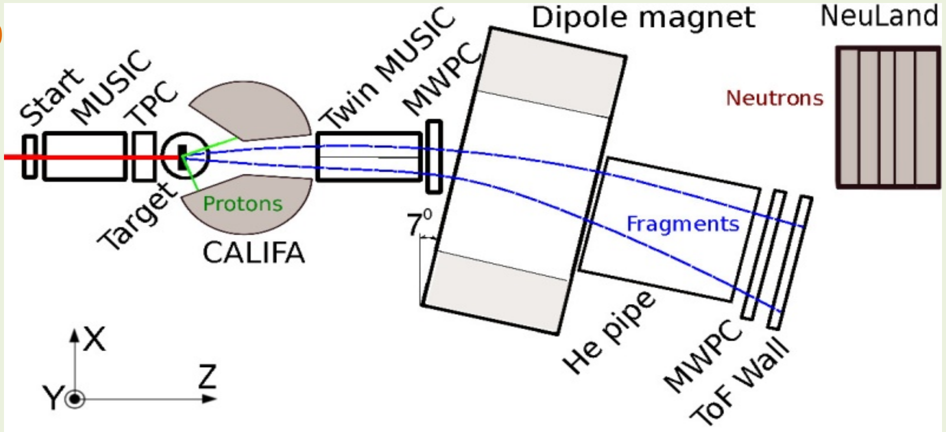
FAIR PHASE 0 → First experiments in June 2018

The R^{3}B a versatile setup for a multipurpose nuclear reactions program

- EM excitations: Low-liying transition strengths, resonances in the continuum, GDR, determinationif astrophysical S factors, …
- Total absorption/Elastic scattering: nuclear radius, nuclear density, …
- Knockout/QFS: evolution of shell structure, N-N correlations, cluster structure, states beyond dripline
- **Hot and dense matter** Equation Of State

…5

  - In contact with the Asyeos collaboration
  - Informal meeting FAZIA-R3B/GLAD (Join WS in Catania February the 19th)
- **Subnucleonic degrees of freedom** Hypernuclei, Nucleon resonances
- **Fission:** structural and dynamic prop



SOFIA + R3B/GLAD
A unique tool to investigate fission controling the excitation energy.

Conclusions

- There is a permanent effort to improve the amount and quality of the data recorded in our experiments
- The guidance of theory is really crucial to design benchmarking experiments able to provide answers to the still open questions in our field
- The structure of the light nuclei is rather well know (or the selection of well known cases)--> usefull to understand the reation mechanism.
- Simultaneous detection of different channels (observables) in the same experiment offer unique possibilities to dissantangle the best description of the reaction mechanisms. As well, the study of the same ¨subject¨ from different experimental approaches, energy regime etc.. would be very interesting
- The critical description of the experimental results from complementary theroretical approaches could also be of extreme interest
- The interplay between structure and reactions is evident.: eventhoug the reaction mechanism is well described, precise structure information is needed to reproduce all the observables

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