ISOLDE Superconducting Recoil Separator

Theoretical nuclear reaction analysis for the ISOLDE Superconducting Recoil Separator (ISRS)

F. Torabi[1*], I. Martel[1], B. V. Carlson[2], N. Keeley[3], and K. Rusek[4]

[1]Departamento de Ciencias Integradas, Facultad de Ciencias Experimentales, Universidad de Huelva, 21071 Huelva, Spain

[2]Departamento de Física, Instituto Tecnológico de Aeronáutica, DCTA, 12228-900, São José dos Campos, SP, Brazil

[3]National Centre for Nuclear Research, ul. Andrzeja Sołtana 7, 05-400, Otwock, Poland

[4]Heavy Ion Laboratory, University of Warsaw, ul. Pasteura 5a, 02-093, Warsaw, Poland

Outline

Introduction

ISRS at ISOLDE and physics cases

Theoretical Framework

Overview of the computational framework and introduction of the codes

Calculations and Results

Residual nuclei and transfer-reaction calculations, cross-sections, and distributions

Summary and Outlook

A summary and future considerations

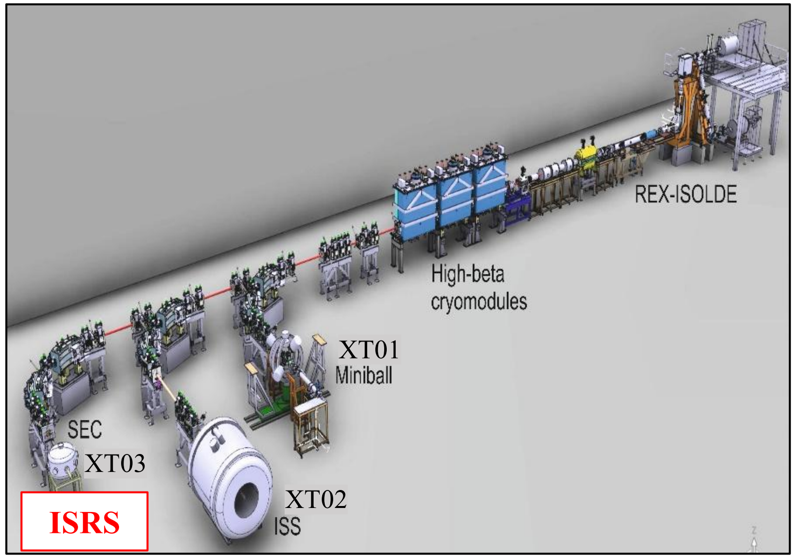
Overview of the ISRS project

What is ISRS?

- *ISRS stands for* ***ISOLDE Superconducting Recoil Separator****.*
- *It is an advanced device being developed to be installed at* ***ISOLDE-CERN*** *to enable studies of* ***exotic nuclei****, especially those that are difficult to detect or separate with current instruments.*

How will ISRS work?

- *Uses* ***superconducting multifunction magnets*** *to bend and focus reaction products.*
- *Features a* ***compact, lightweight design*** *with very high resolution.*
- *Includes a* ***compact ring*** *to store and guide ions.*

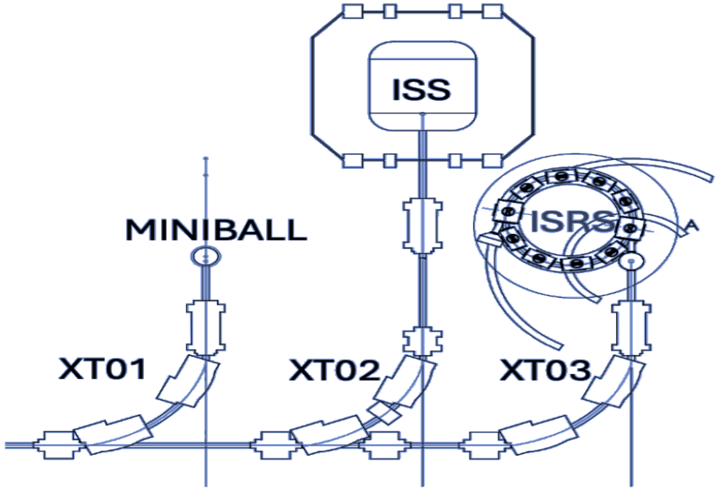


What kind of science will it enable?

- ***Nuclear structure*** *(shells, halos, exotic decays)*
- ***Astrophysics*** *(r-process, nucleosynthesis)*
- ***Reaction mechanisms*** *(breakup, transfer, fusion)*

First step: Ion Test Bench (IONTB)

- *That* ***first step*** *in making the ISRS a reality*
- *The IONTB is a* ***prototype experimental setup*** *at ISOLDE.*



Ion Test Bench (IONTB)

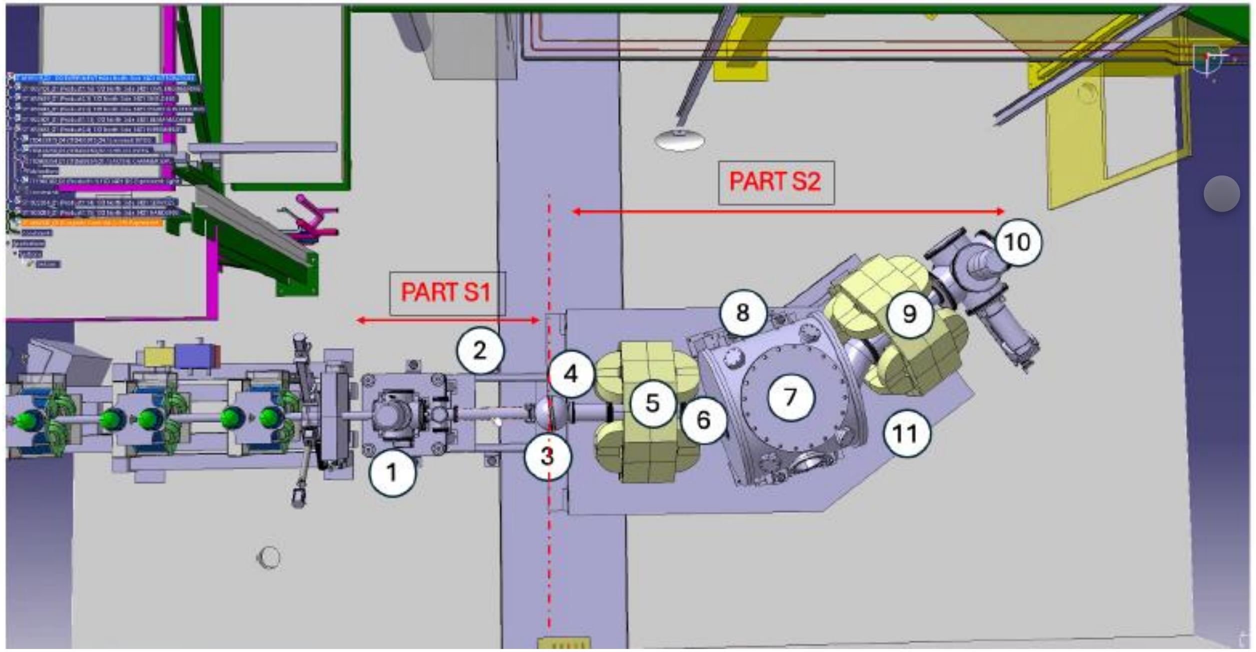
ISRS Project
Long-term project

IONTB
First experimental step of the ISRS project

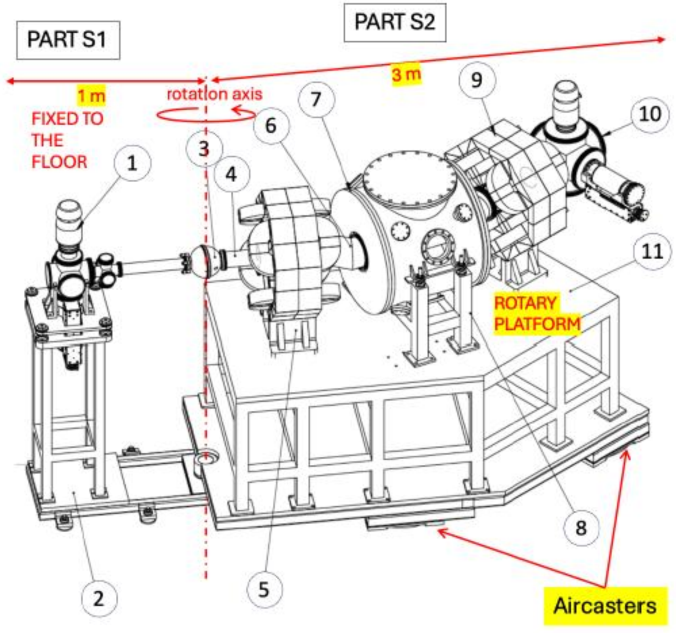
MAGDEM
Superconducting magnet

Timeline
LS3 (2026–2028)

Future
Operations from **2028**



Location of IONTB at HIE-ISOLDE (XT03)



Schematics of the prototype IONTB, composed of parts S1 and S2. Main subsystems: 1-Differential pumping, 2-Fixed platform, 3-Reaction chamber, 4-Beam line, 5-Quadrupole magnet, 6-Beam line, 7-MAGDEM superconducting magnet, 8-Mechanical support, 9-Quadrupole magnet, 10-Focal plane chamber, 11-Rotary platform with air-casters.

For more detailed information about the ISRS project, please visit: https://www.uhu.es/isrs/

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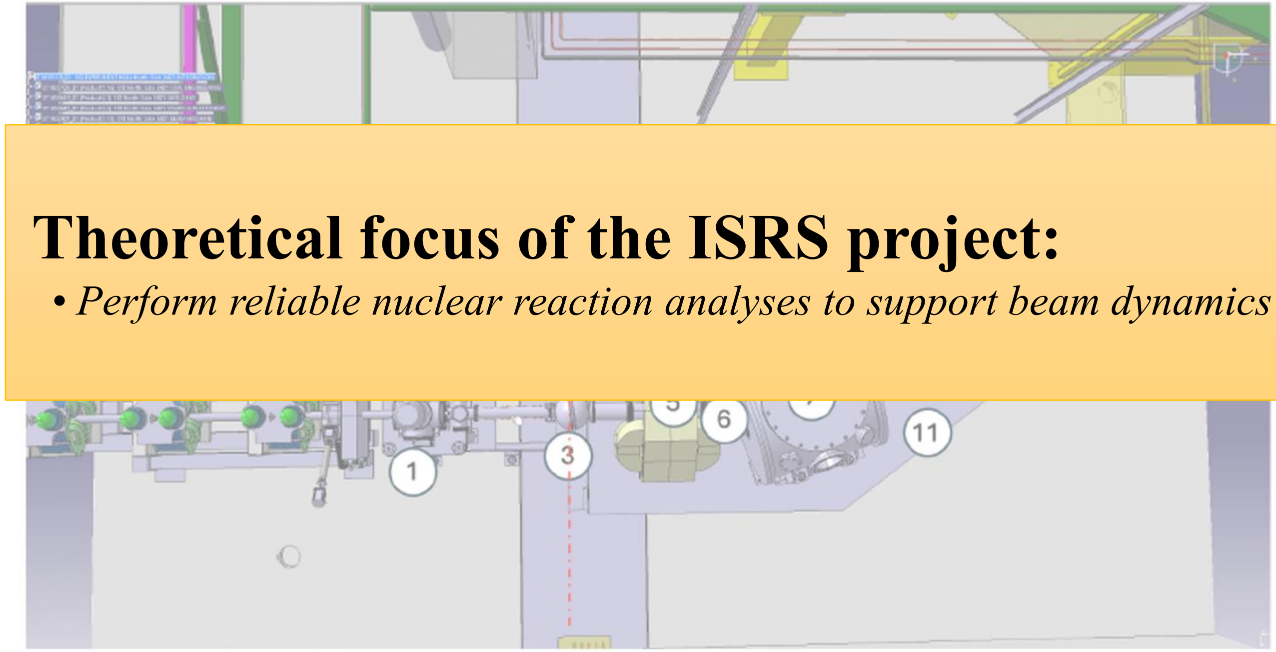

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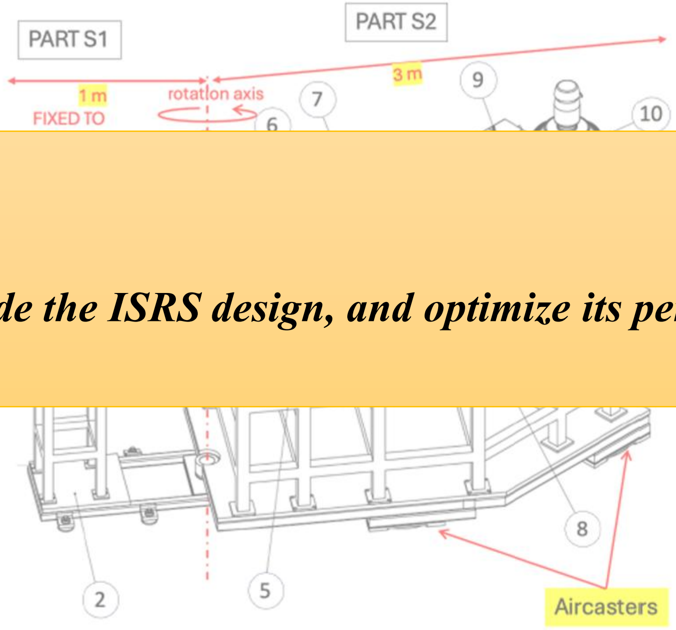

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Theoretical focus of the ISRS project:

- *Perform reliable nuclear reaction analyses to support beam dynamics simulations,* ***guide the ISRS design, and optimize its performance.***

For more detailed information about the ISRS project, please visit: https://www.uhu.es/isrs/

Selection of physics cases

The main goal of the nuclear reaction studies within the ISRS project is to conduct detailed investigations of reaction mechanisms across a broad range of projectile–target systems. The primary objectives include:

- **Residual nuclei production**
- **Contributions of individual mechanisms**

Single and multinucleon transfer reactions
Coulomb excitation
Complete and incomplete fusion
Compound-nucleus decay: fusion–evaporation

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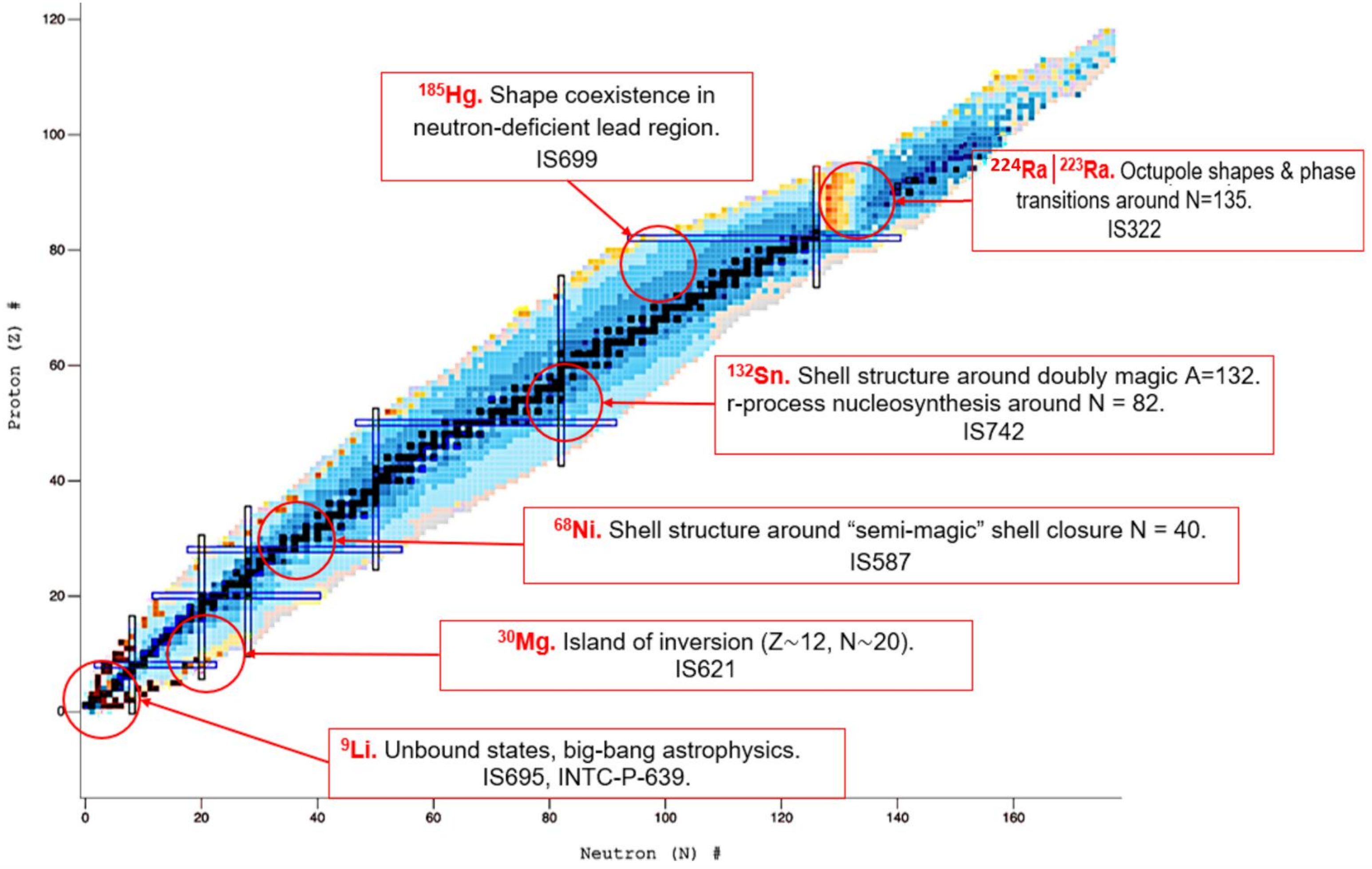
Initial systems under study

- Selected based on the approved ISOLDE experimental proposals.
- Using **CD_2** as the target.
- Radioactive beams: **^{9}Li, ^{30}Mg, ^{68}Ni, ^{132}Sn, ^{185}Hg, and ^{224}Ra**.
- Beam energies: **5 and 10 MeV/u**.



Computational framework for reaction analysis

A crucial initial step in our nuclear reaction analyses is to develop a comprehensive computational framework that accurately describes cross sections using established nuclear reaction codes.

✓ **FRESCO — Elastic & Transfer Reactions** *Ian J. Thompson, Comput. Phys. Rep. 7 (1988) 167.*

- *This versatile coupled-channels code is widely used for direct nuclear reaction calculations, supporting elastic scattering, inelastic excitation, transfer reactions, and breakup processes.*

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✓ **PACE4 — Fusion-Evaporation** *A. Gavron, Phys. Rev. C 21, 230 (1980).*

❑ *Evaporation-focused Monte Carlo code for projectile absorption.*

✓ **EMPIRE — Detailed Reaction Cross-Sections** *M. Herman, et al, Nucl. Data Sheets 108, 2655 (2007).*

❑ *First released in 1980, EMPIRE has been continuously improved over time.*

❑ *It includes key nuclear reaction models: Coupled Channels, DWBA, exciton model, Hauser-Feshbach, etc.*

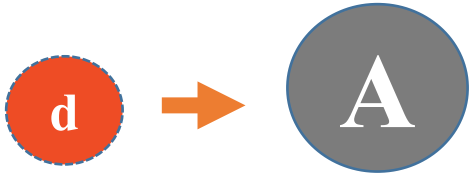
❑ *Equipped with an extensive input parameter library covering nuclear masses, optical parameters, deformations, discrete levels, etc.*

❑ *The **modified version** integrated DWBA-IAV to estimate the inclusive breakup cross sections.*

Nuclear Reactions: General approach

Deuteron-induced reactions

Extensive theoretical and experimental studies have been conducted on the inclusive neutron and proton emission cross sections in deuteron-induced reactions. Yet, the analysis of these reactions continues to be a challenging problem.



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$d = n + p$

$d + A \rightarrow p + B$

B is any possible configuration of the n + A system

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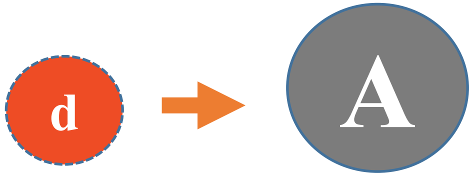

ELASTIC BREAKUP (EBU)

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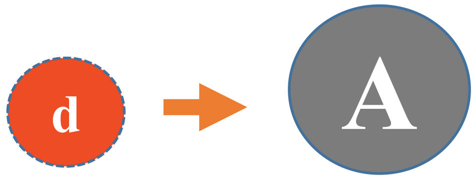

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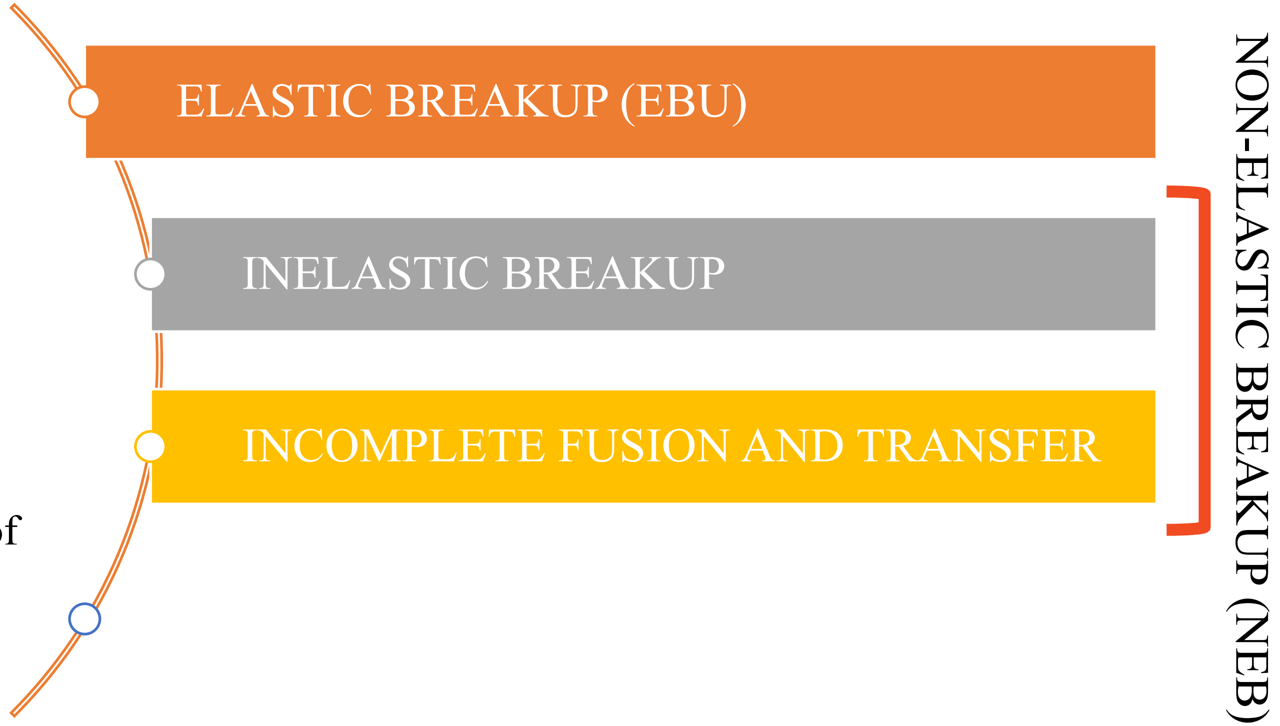

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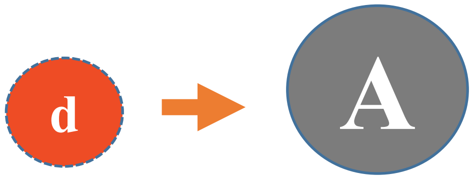

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- ELASTIC BREAKUP (EBU)
- INELASTIC BREAKUP
- INCOMPLETE FUSION AND TRANSFER
- COMPLETE FUSION

NON-ELASTIC BREAKUP (NEB)

DWBA-IAV for breakup

Use of the post-form distorted wave Born approximation of the Ichimura-Austern-Vincent approach (DWBA-IAV) to describe breakup:

For A(d, p)X (p detected; X= n + A represents a final state of the fragment n together with the target), the inclusive breakup cross sections are obtained as:

$$\frac{d^2\sigma}{d\Omega_p dE_p} = \frac{d^2\sigma^{EBU}}{d\Omega_p dE_p} + \frac{d^2\sigma^{NEB}}{d\Omega_p dE_p}$$

The contribution due to elastic breakup (EBU):

$$\frac{d^2\sigma^{EBU}}{d\Omega_p dE_p} = \frac{2\pi}{\hbar v_d}\rho_p(E_p)\int |T(\vec{k}_p, \vec{k}_n; \vec{k}_d)|^2 \delta(E_d + \varepsilon_d - E_p - E_n) d\vec{k}_n$$

G. Baur, F. Rösel, D. Trautmann and R. Shyam, Phys. Rep. 111,333 (1984).
M. Ichimura, N. Austern, and C. M. Vincent, Phys. Rev. C 32, 431 (1985).
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The T-matrix element is approximated by the post-form of the DWBA matrix element

$$T(\vec{k}_p, \vec{k}_n; \vec{k}_d) = \left\langle \tilde{\chi}_p^{(-)}(\vec{k}_p, \vec{r}_p)\tilde{\chi}_n^{(-)}(\vec{k}_n, \vec{r}_n) \,|v_{np}(\vec{r})|\, \chi_d^{(+)}(\vec{k}_d, \vec{R})\phi_d(\vec{r}) \right\rangle$$

Which can be well-approximated within the **zero-range DWBA** by including a correction for finite-range effect as

$$T(\vec{k}_p, \vec{k}_n; \vec{k}_d) = D_0 \left\langle \tilde{\chi}_p^{(-)}(\vec{k}_p, a\vec{R})\tilde{\chi}_n^{(-)}(\vec{k}_n, \vec{R})\Lambda(R) \,|\, \chi_d^{(+)}(\vec{k}_d, \vec{R}) \right\rangle$$

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Following IAV work, the nonelastic component is also added as follows:

The nonelastic breakup (NEB) contribution is obtained from the imaginary part of the optical potential between the absorbed fragment and the target as

$$\frac{d^2\sigma^{NEB}}{d\Omega_p dE_p} = -\frac{2}{\hbar v_d}\rho_b(E_B)\left\langle \Psi_n(\vec{k}_p,\vec{r}_n;\vec{k}_d)\middle| W_n\left(\vec{r}_n\right)\middle|\Psi_n(\vec{k}_p,\vec{r}_n;\vec{k}_d)\right\rangle$$

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$$\left|\Psi_n(\vec{k}_p,\vec{r}_n;\vec{k}_d)\right\rangle = \left(\tilde{\chi}_p^{(-)}(\vec{k}_p,\vec{r}_p)G_n^{(+)}\left(\vec{r}_n,\vec{r}_n'\right)|v_{pn}(\vec{r})|\,\chi_d^{(+)}(\vec{k}_d,\vec{R})\phi_d(\vec{r})\right\rangle$$

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EMPIRE

To accurately describe the inclusive cross sections, the role of preequilibrium and equilibrium processes should also be taken into account:

Exciton model: preequilibrium emissions

nucleons are emitted before the energy is equally distributed.

The module PCROSS includes the preequilibrium mechanism as defined in the exciton model.

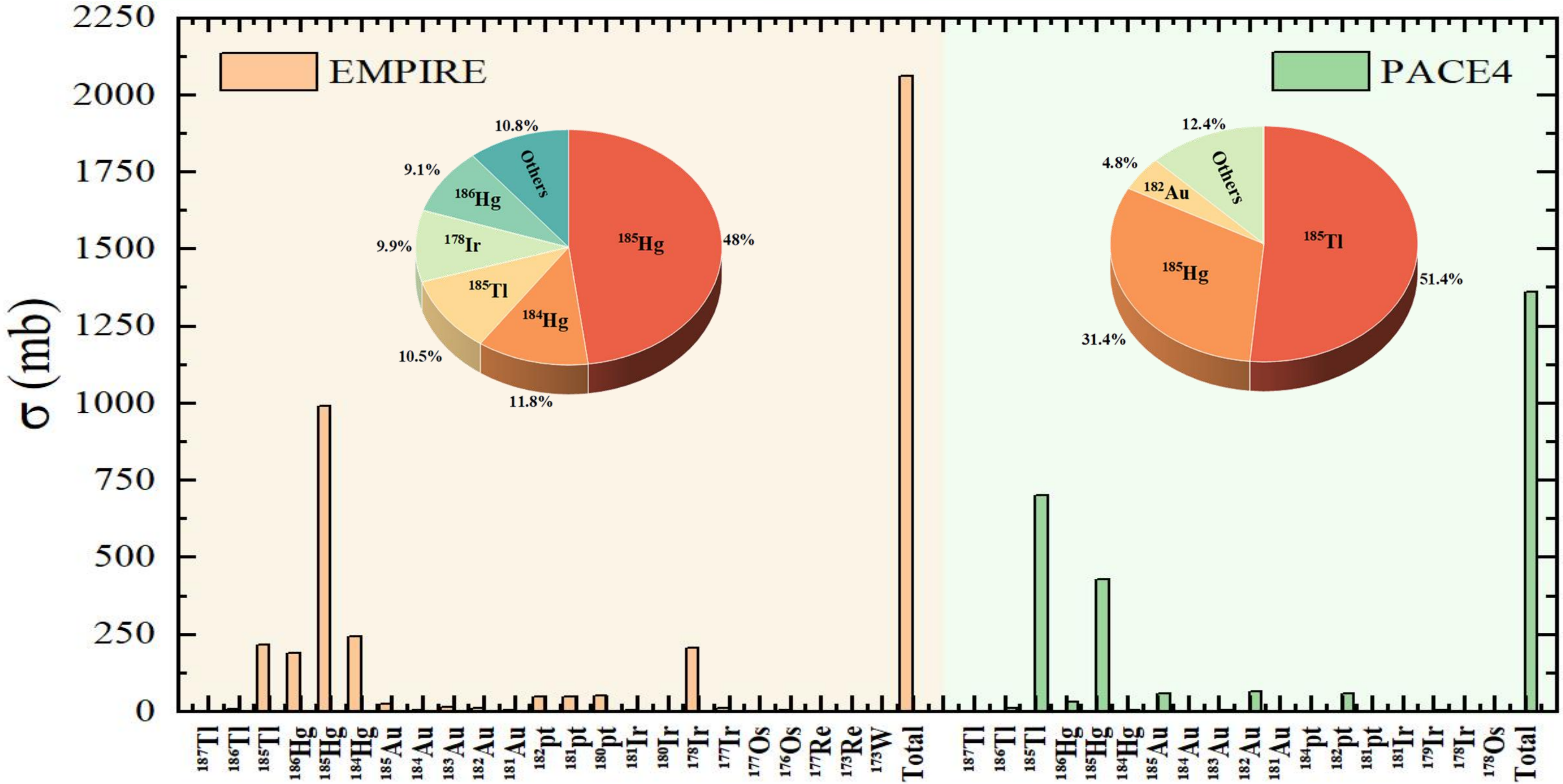
The statistical model: equilibrium emissions

The statistical model used in the EMPIRE is based on the Hauser-Feshbach formalism.

The emission of neutrons, protons, alpha particles, deuterons, tritons, and He-3 is taken into account along with the competing fission channel.

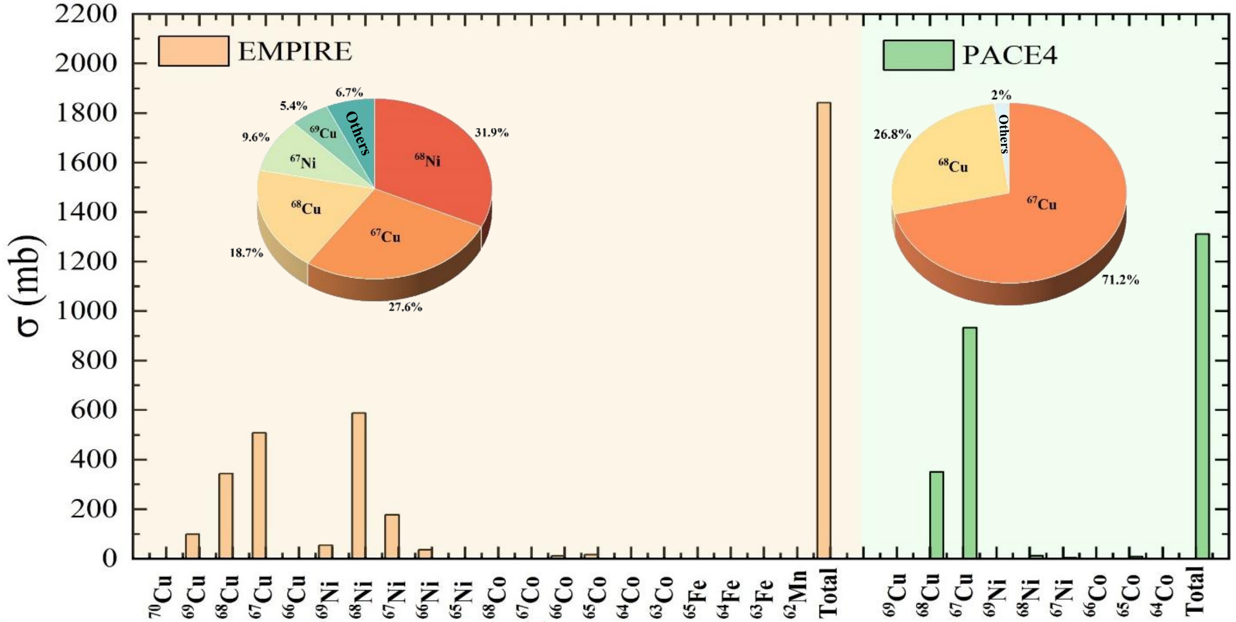
Yields of residual nuclei-EMPIRE, PACE4

^{185}Hg+d
Energy=10 MeV/u

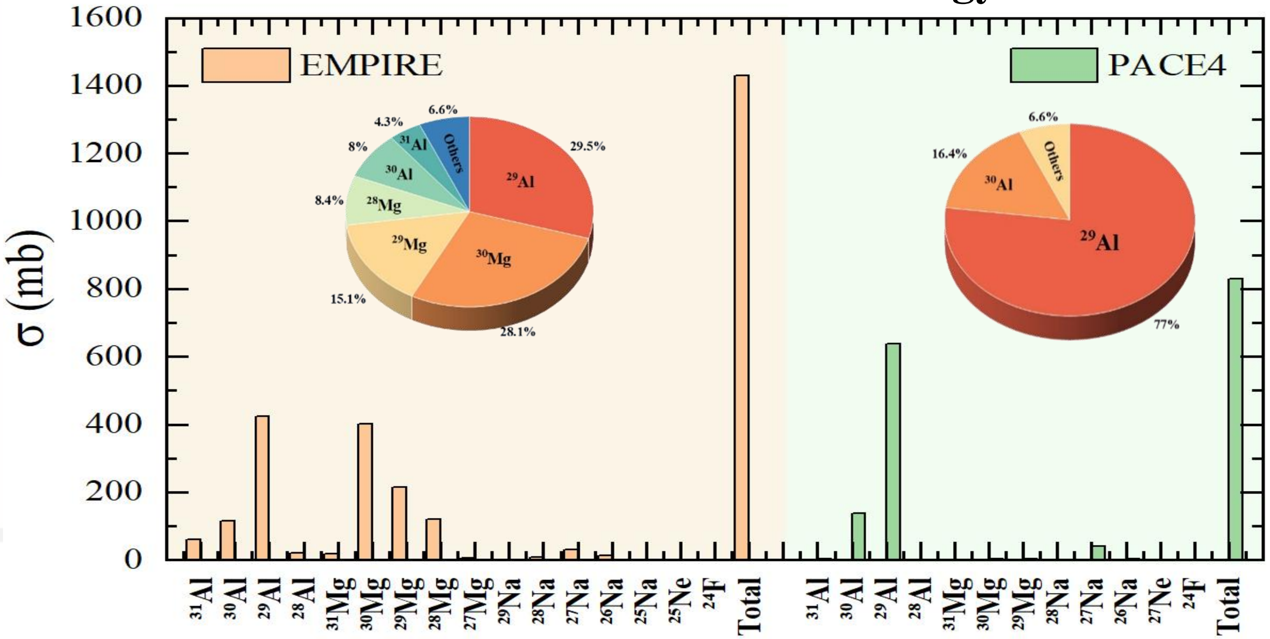


Yields of residual nuclei-EMPIRE, PACE4

^{68}Ni+d
Energy=10 MeV/u



^{30}Mg+d
Energy=10 MeV/u



Yields of residual nuclei-EMPIRE, PACE4

❑ EMPIRE:

- ***Comprehensive nuclear reaction modeling*** *across various projectiles and energy ranges.*
- ***The code accounts for the major nuclear reaction mechanisms,*** *including DWBA-IAV, pre-equilibrium, and compound nucleus, enabling detailed estimation of individual contributions.*
- ***Accounts for the emission of neutrons, protons, deuterons, tritons, He-3, and alpha particles****.*
- ***Utilizes an extensive library of input parameters from RIPL-3****.*
- ***Requires complex setup and detailed parameter tuning****.*
- ***Slower than lightweight codes but highly versatile*** *for diverse reaction types and detailed studies.*

❑ PACE4:

- ***Evaporation-focused Monte Carlo code*** *for modelling compound nucleus decay.*
- ***PACE4 is efficient for evaporation-dominated reactions,*** *providing rapid statistical-model calculations with a simplified setup, and is capable of generating approximate angular distributions of evaporation residual nuclei in inverse kinematics.*
- ***Specializes in the emission of neutrons, protons, alpha particles, and gamma rays*** *from the compound nucleus.*
- ***User-friendly****, with a straightforward parameter input format.*
- ***Limited in handling complex reaction mechanisms****, such as pre-equilibrium processes or direct reactions.*

Angular and Energy distributions

Angular and energy distributions of the residual nuclei were computed for each reaction. These results are used as inputs to beam-dynamics simulations to optimize ISRS performance. To generate these distributions:

- *Used PACE4 to simulate angular distributions (strong forward-peaking distributions)* $f(\theta)$.
- *Applied Gaussian fits, normalized to EMPIRE cross sections.*
- *Fitted energy spectra with normalized Gaussians (as probability distributions)* $g(E)$.
- *Final distribution:* $h(\theta, E) = f(\theta). g(E)$

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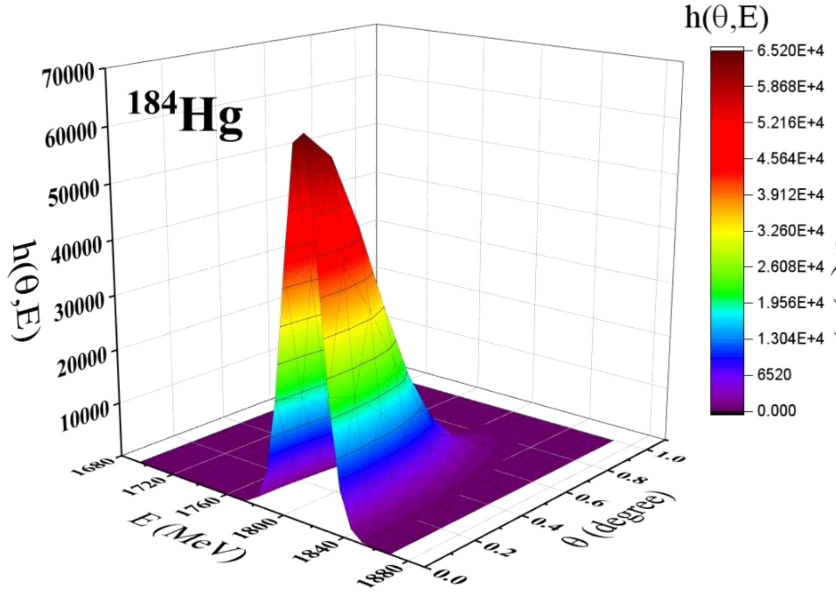
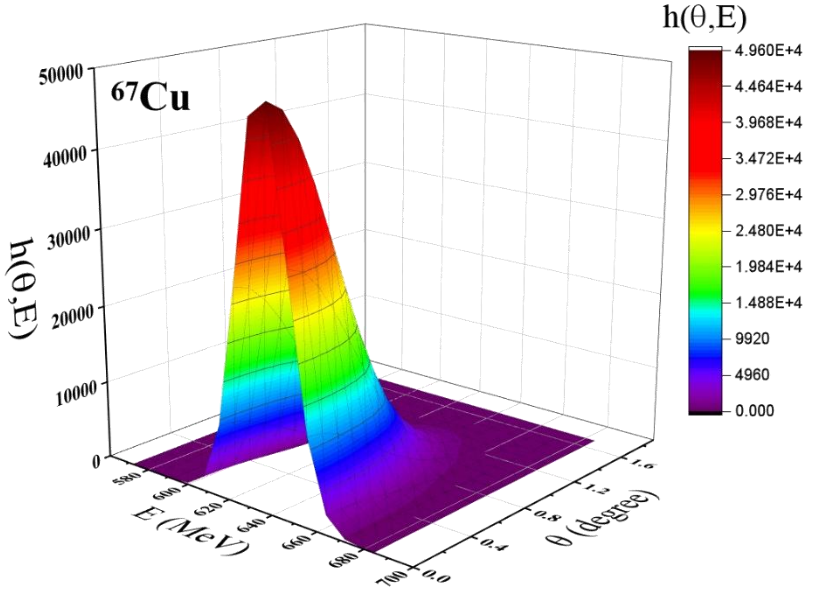
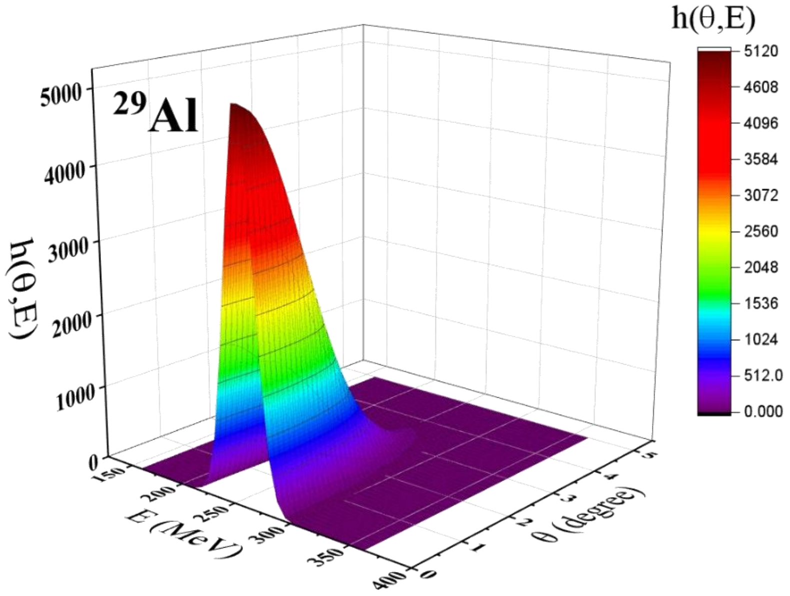


^{184}Hg produced in the ^{185}Hg + d reaction.



^{67}Cu produced in the ^{68}Ni + d reaction.



^{29}Al produced in the ^{30}Mg + d reaction.

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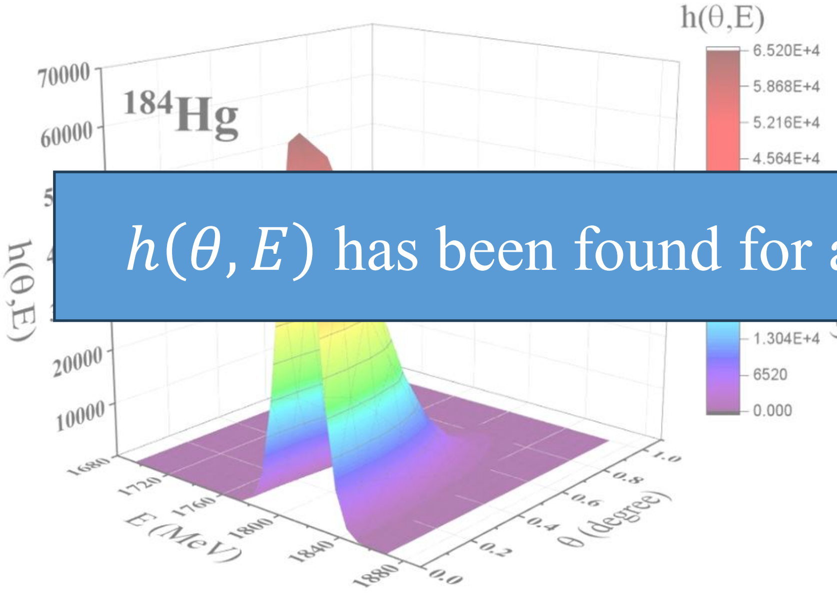
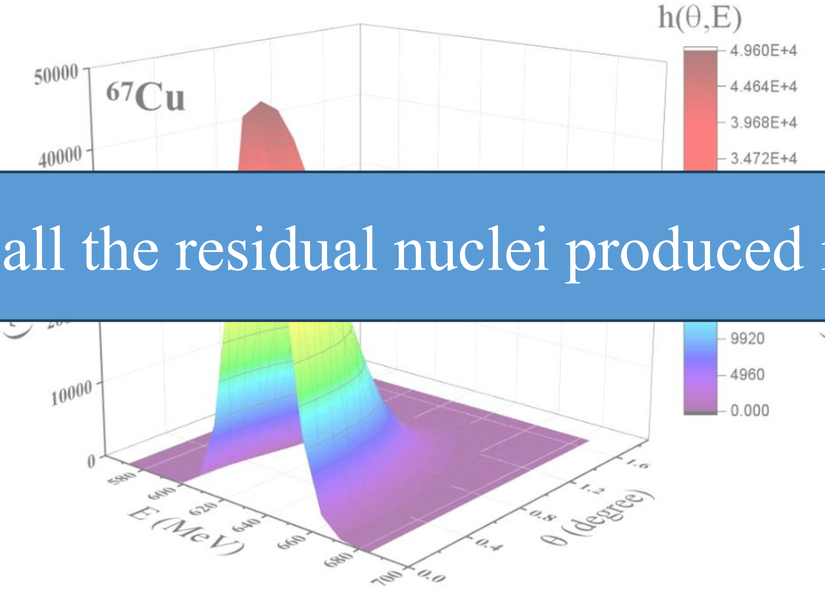
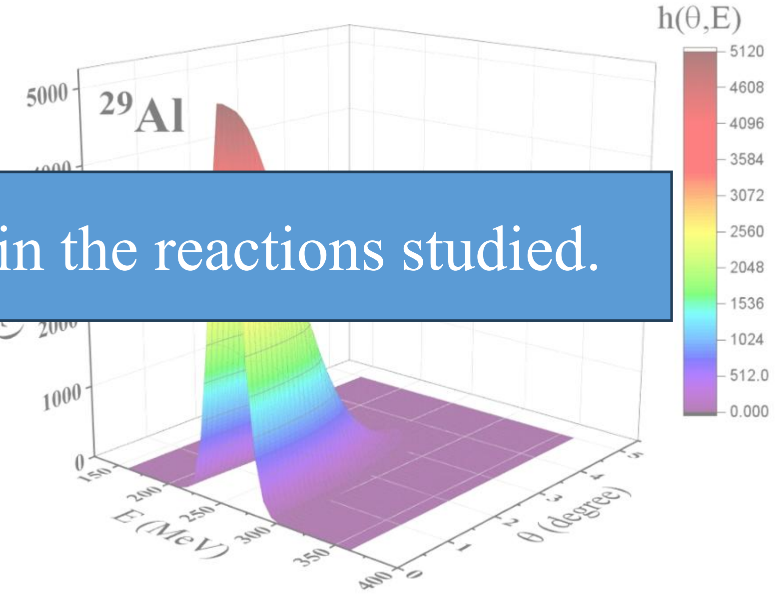




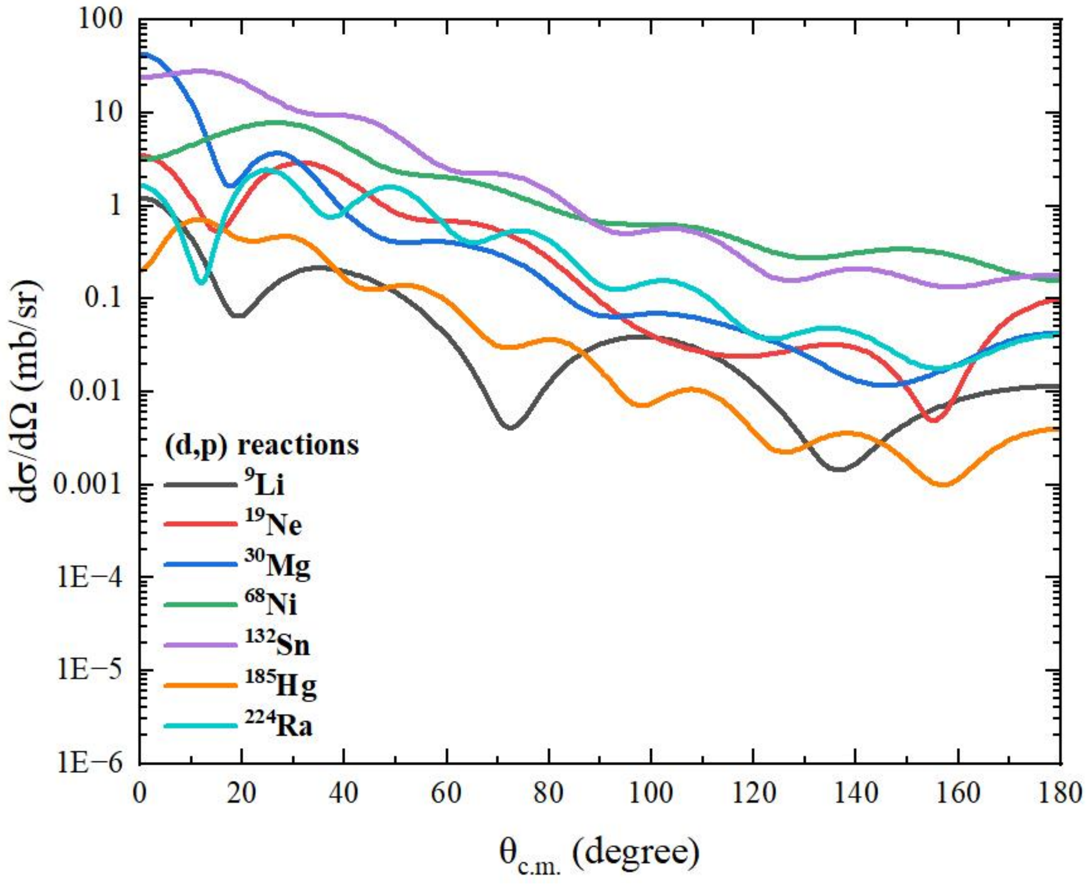


$h(\theta, E)$ has been found for all the residual nuclei produced in the reactions studied.

^{184}Hg produced in the ^{185}Hg + d reaction. ***^{67}Cu produced in the ^{68}Ni + d reaction.*** ***^{29}Al produced in the ^{30}Mg + d reaction.***

Transfer reaction calculations with FRESCO

Studied **(d,p)** and **(d,n)** reactions on selected physics cases **(^{9}Li, ^{19}Ne, ^{30}Mg, ^{68}Ni, ^{132}Sn, ^{185}Hg, ^{224}Ra)** at **10 MeV/u**.



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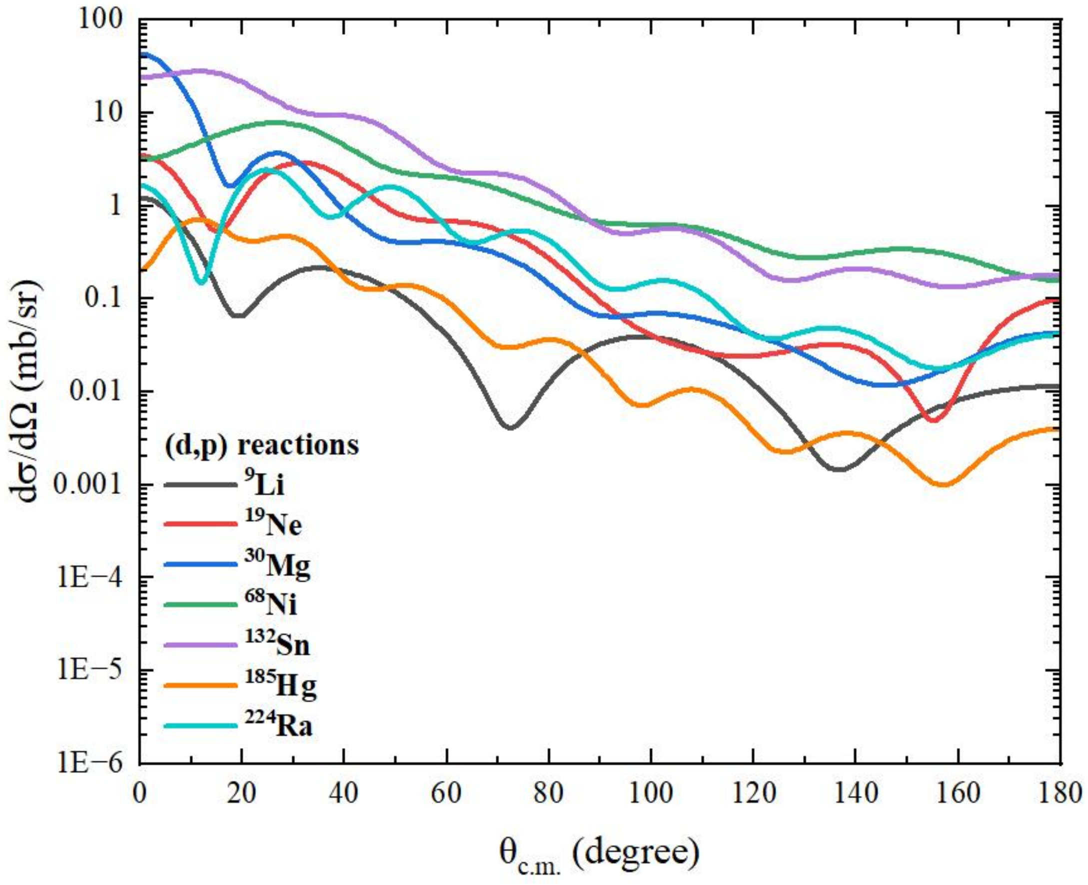
- ❑ Focused on ground-state to ground-state transitions, and for some CRC applied specific cases.
- ❑ Optical potentials were tested for the entrance and exit channels.
- ❑ Final results used An-Cai (d) and Koning-Delaroche (p/n) potentials.
- ❑ Differential cross sections (lab & c.m.) and kinematics plots provided for all cases.



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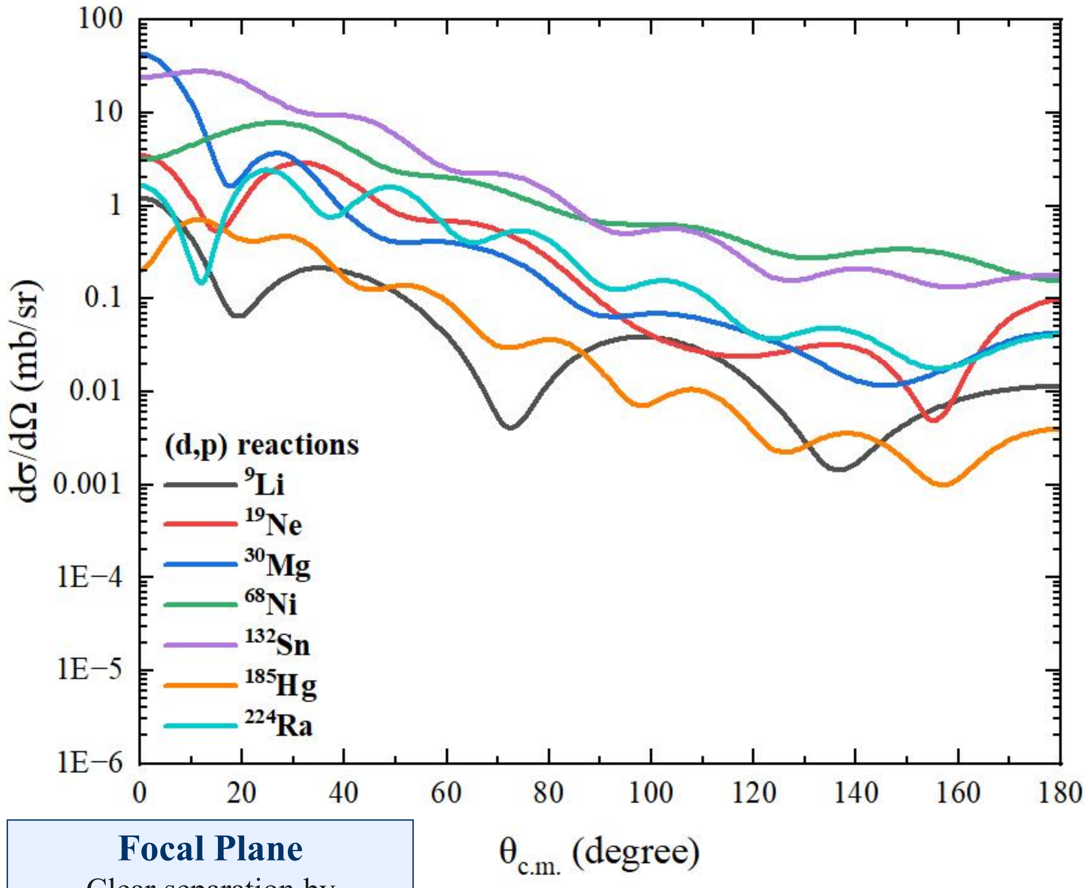
Studied **(d,p)** and **(d,n)** reactions on selected physics cases (**^{9}Li, ^{19}Ne, ^{30}Mg, ^{68}Ni, ^{132}Sn, ^{185}Hg, ^{224}Ra)** at **10 MeV/u**.

- ❑ Focused on ground-state to ground-state transitions, and for some CRC applied specific cases.
- ❑ Optical potentials were tested for the entrance and exit channels.
- ❑ Final results used An-Cai (d) and Koning-Delaroche (p/n) potentials.
- ❑ Differential cross sections (lab & c.m.) and kinematics plots provided for all cases.



Reaction Calculations
Cross sections and distributions

→ **Monte Carlo Sampling**
Generate virtual ions

→ **ISRS Tracking**
Different mass & charge → different path

→ **Focal Plane**
Clear separation by position, B_ρ, TOF, energy, scattering angle

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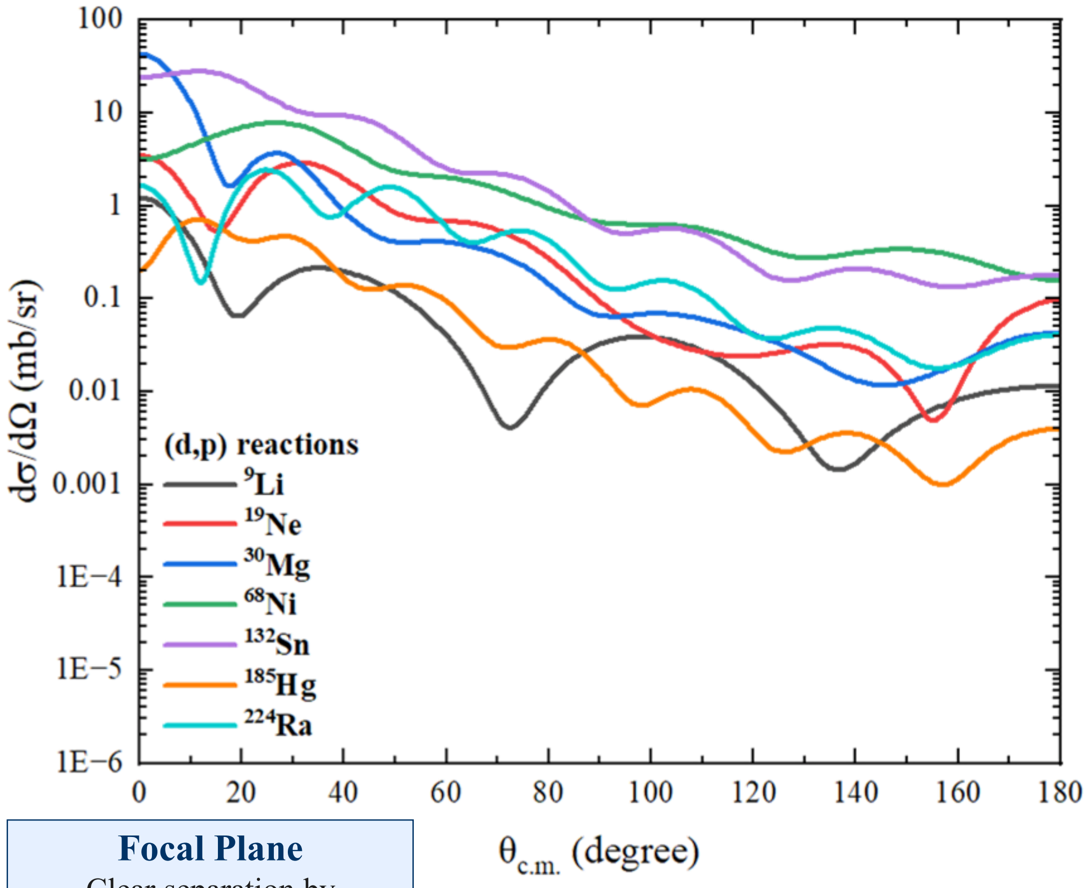

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^{19}Ne ⟹ ion test bench ⟹ (day 1 experiment).

Summary and outlook

Theoretical Framework

- *Integrated workflow using an enhanced version of EMPIRE (DWBA–IAV), PACE4, and FRESCO to produce cross sections and kinematic distributions for selected physics cases.*

Residual Nuclei Production

- *Residual nuclei were analysed with EMPIRE & PACE4 → Gaussian angular and energy distributions extracted → Exported to beam dynamics simulations → ISRS optimization*

Transfer Reaction Studies

- *(d,p) and (d,n) reactions investigated with FRESCO → Beams: ^{9}Li, ^{30}Mg, ^{68}Ni, ^{132}Sn, ^{185}Hg, ^{224}Ra at 10 MeV/u → Results prepared for ISRS beam dynamics simulation*

NEXT STEPS: Shape the working physics group

- *Our work continues with the expansion of theoretical modelling for reaction analysis, aiming to explore a broader range of physics cases of interest.*

- *We are establishing the ISRS Physics Working Group to shape the scientific program of the ISOLDE Superconducting Recoil Separator (ISRS) and to incorporate additional physics cases for future analysis. This group will play a central role in developing a focused program of high-precision studies in nuclear structure, astrophysics and reaction dynamics, to be carried out using ISRS.*

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https://www.uhu.es/isrs/isrs-physics-working-groups/

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MINISTERIO DE CIENCIA E INNOVACIÓN

Plan de Recuperación, Transformación y Resiliencia

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ISOLDE Superconducting Recoil Separator