

A comprehensive study of the main reaction channels in reactions involving weakly bound nuclei

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University of São Paulo, Brasil

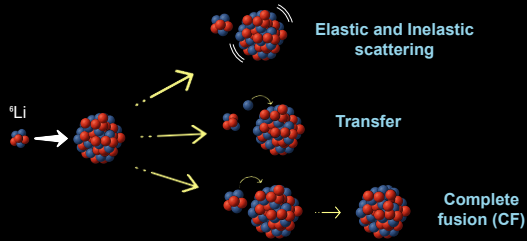
Supervisors: Dr. Leandro Gasques and
Dr. Andres Arazi (TANDAR-CNEA, Argentina)



Motivation

Weakly bound nuclei: ${}^6\text{Li} \rightarrow \alpha + \text{d}$ ($E_B = 1.474$ MeV) & ${}^7\text{Li} \rightarrow \alpha + \text{t}$ ($E_B = 2.467$ MeV)

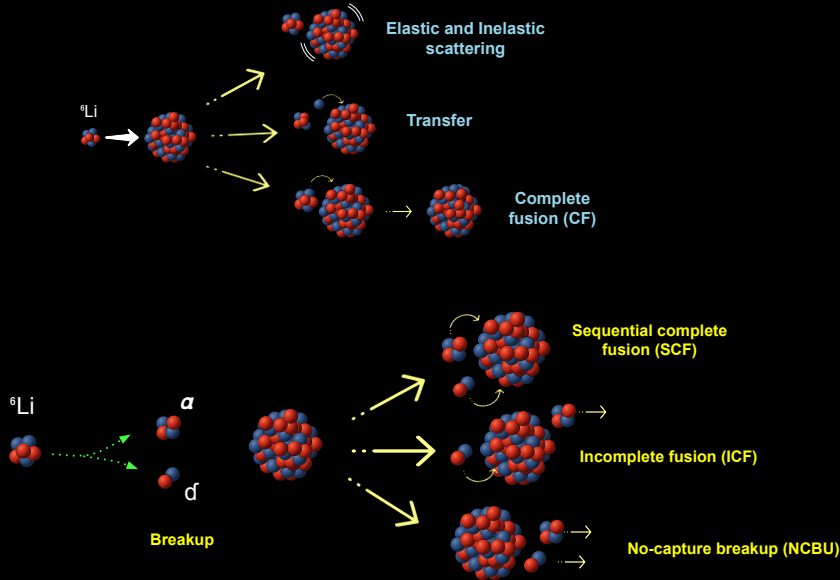
- High probability of breakup
- Three-body or many-body problem.



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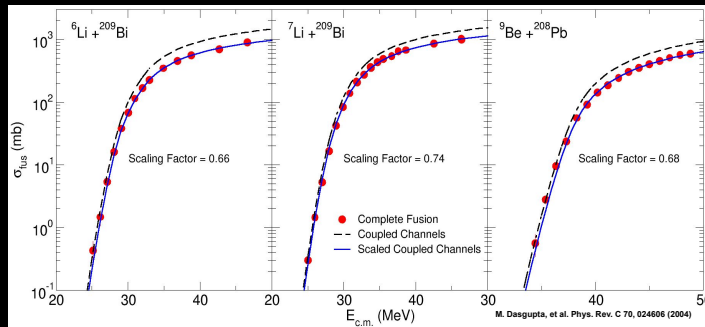
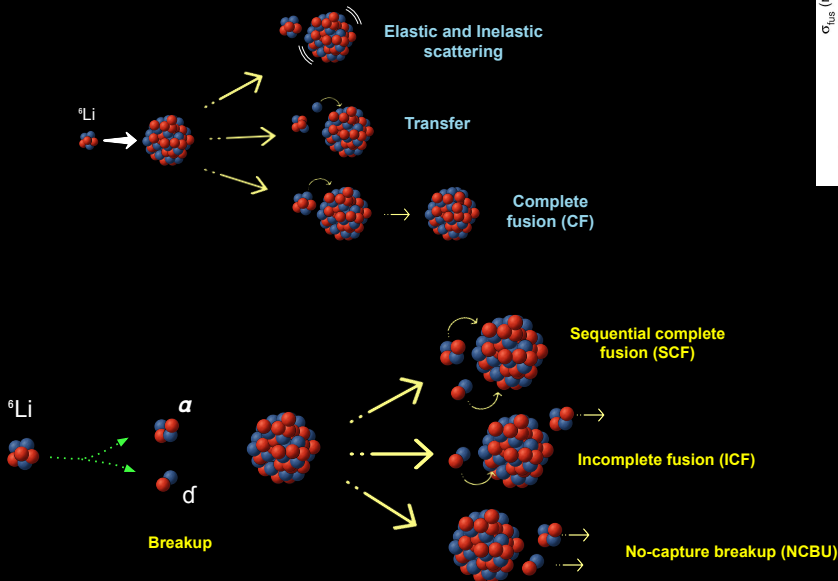
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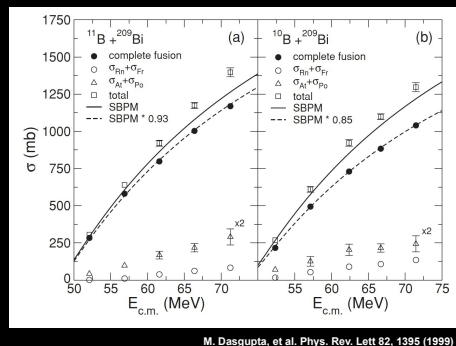
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→Suppression in the complete fusion (CF) experimental cross section compared with theoretical predictions.

→Observed in reactions involving weakly bound nuclei.

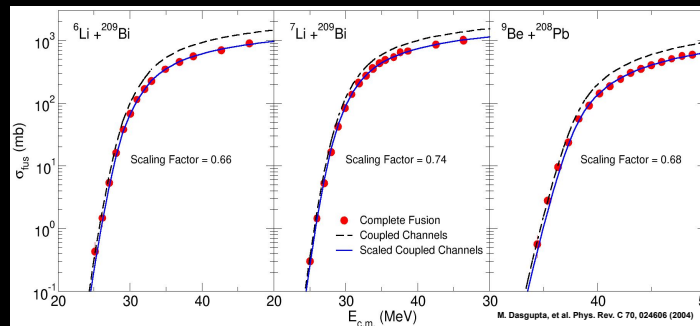
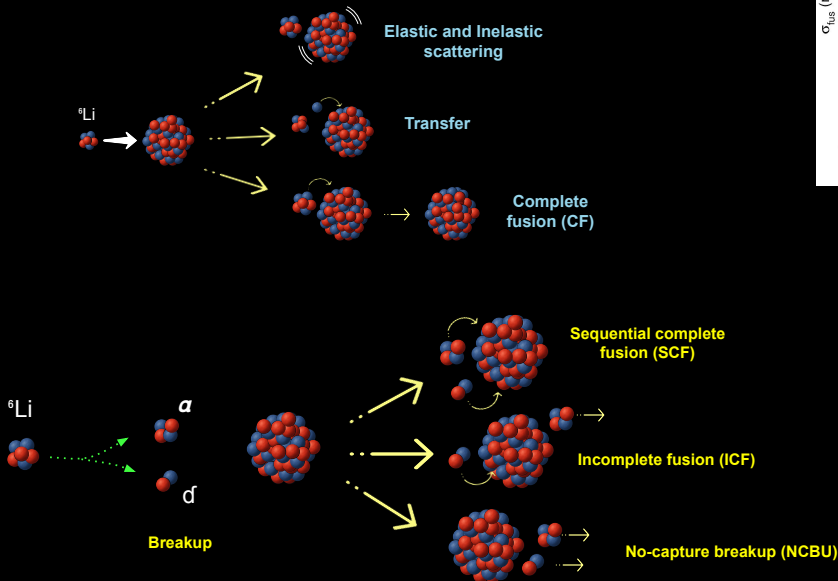


→The CF is mainly reduced by breakup, which favors incomplete fusion (ICF).

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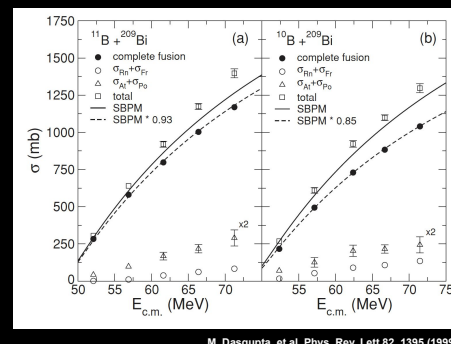
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→The CF is mainly reduced by breakup, which favors incomplete fusion (ICF).

How can the influence of the breakup mechanism on the other reaction channels be understood?

→Systematic investigation of reactions involving nuclei of this nature.

LAFNA-USP systematic program on weakly bound beams:



Objectives

- Study the main reaction channels for ${}^{6,7}\text{Li} + {}^{124}\text{Sn}$ and ${}^6\text{Li} + {}^{196}\text{Pt}$.
- Deepen the understanding of reaction mechanisms involving weakly bound nuclei.
- Perform a **simultaneous analysis** of all channels, essential to describe collisions near the Coulomb barrier.

${}^6,7\text{Li} + {}^{124}\text{Sn}$ - experiment

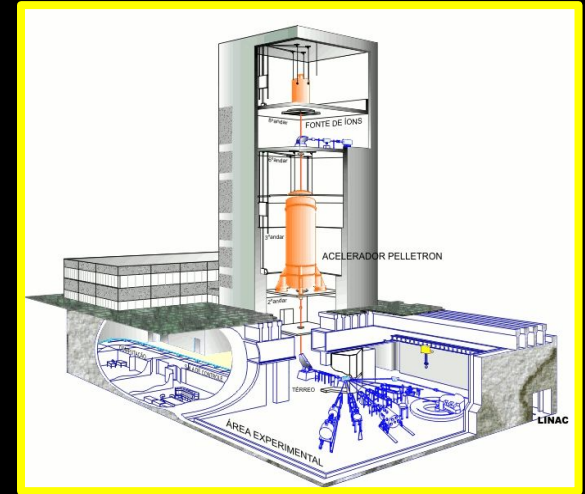
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- Elastic and inelastic scattering
- Nucleon transfer reactions
- ${}^6\text{Li} + {}^{124}\text{Sn}$ @ 18.24 and 21.5 MeV, $V_{\text{B(Lab)}} = 20.2$ MeV
- ${}^7\text{Li} + {}^{124}\text{Sn}$ @ 18.24 and 21.3 MeV, $V_{\text{B(Lab)}} = 19.9$ MeV



Pelletron accelerator (São Paulo)
Tandem Van de Graaff — 8 MV

$6,7\text{Li} + {}^{124}\text{Sn}$

PHYSICAL REVIEW C **108**, 044602 (2023)



Comprehensive study of the $6,7\text{Li} + {}^{124}\text{Sn}$ reactions at energies near the Coulomb barrier

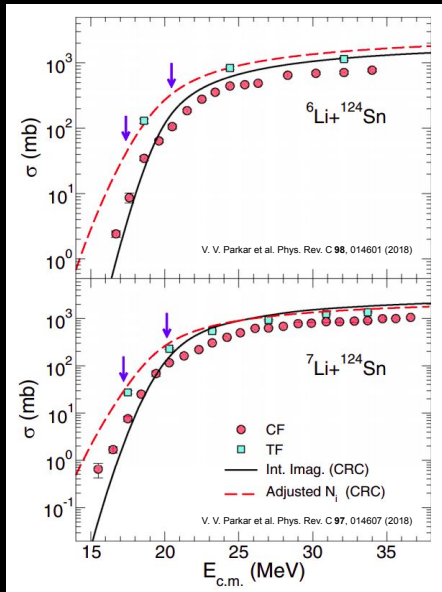
J. K. L. Chaves¹, L. R. Gasques^{1,2}, L. C. Chamon¹, V. Scardigli¹, A. Lépine-Szily¹, W. A. Y. Hatano¹, and V. A. B. Zagatto²

¹Instituto de Física, Universidade de São Paulo, Rua do Matao 1371, 05508-090 São Paulo, São Paulo, Brazil

²Instituto de Física da Universidade Federal Fluminense, 24210-346 Niterói, Rio de Janeiro, Brazil

(Received 31 August 2023; accepted 22 September 2023; published 3 October 2023)

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- CRC calculations with SPP reproduce TF data.
- CF suppression observed above the barrier \rightarrow ICF contribution.

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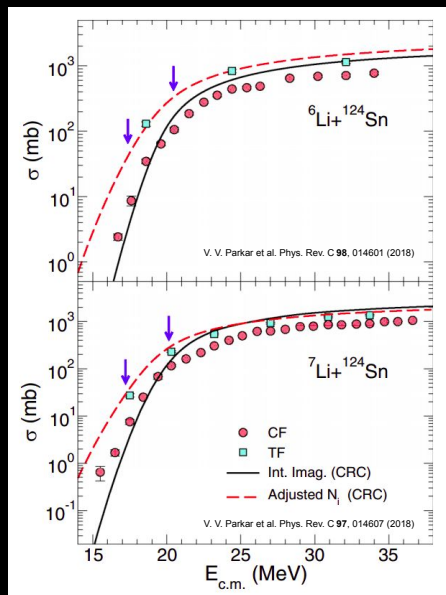
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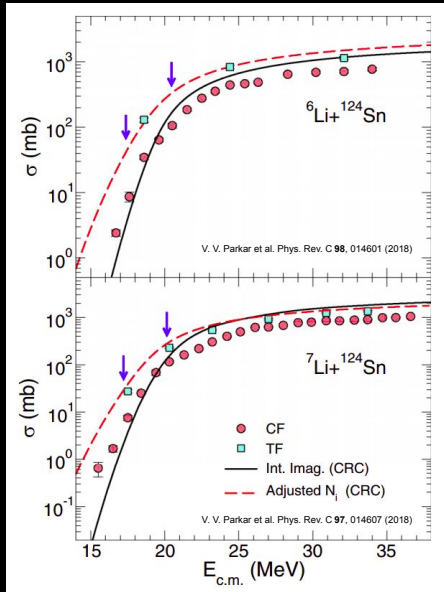
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${}^6\text{Li} + {}^{196}\text{Pt}$

- Complete fusion
- Nucleon transfer reactions
- ${}^6\text{Li} + {}^{196}\text{Pt}$ @ 20 - 36 MeV, $V_{B(\text{Lab})} = 28.4$ MeV.



Comisión Nacional de Energía Atómica




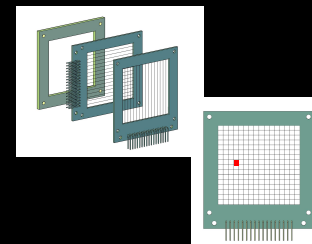
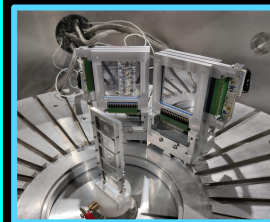
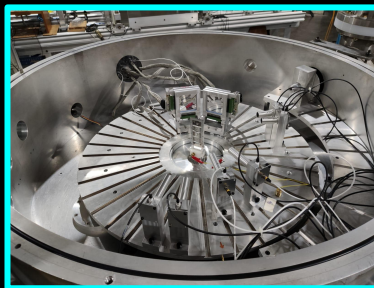
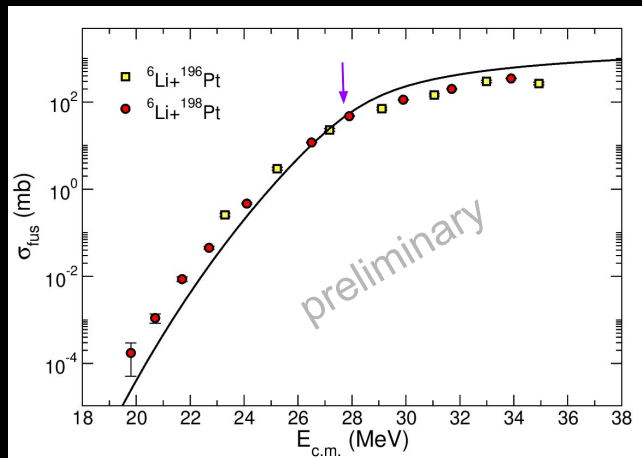
TANDAR accelerator (Buenos Aires)
Tandem Van de Graaff — 14 MV

Preliminary results

- Transfer channel :
 - 1n stripping
 - 1p pickup under investigation (^{199}r ?)
- Fusion-evaporation

- Elastic and inelastic scattering
- Nucleon transfer reactions
- ${}^6\text{Li} + {}^{196}\text{Pt}$ @ 24, 26, 28, 30 MeV

 Pelletron accelerator (São Paulo)




Detector (50 mm \times 50 mm) mounted in a triple telescope configuration;

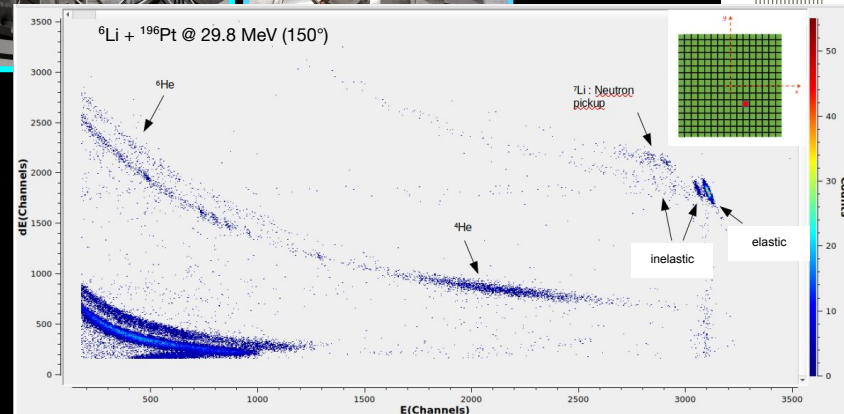
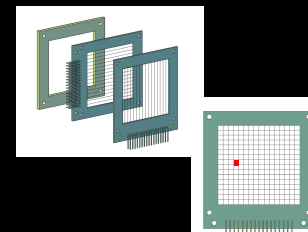
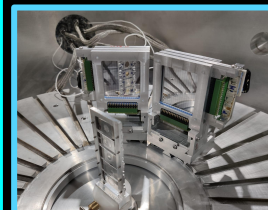
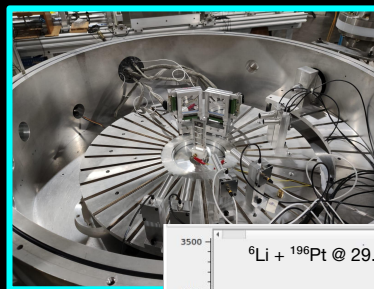
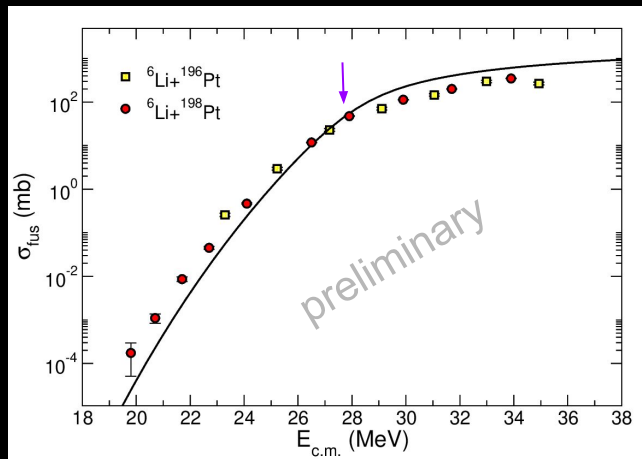
- Two Single Silicon Strip Detectors (SSSD);
- One large area detector with 1000 μm thickness;
- Detectors spaced 40° apart, each covering an angular range of 25° .

Preliminary results

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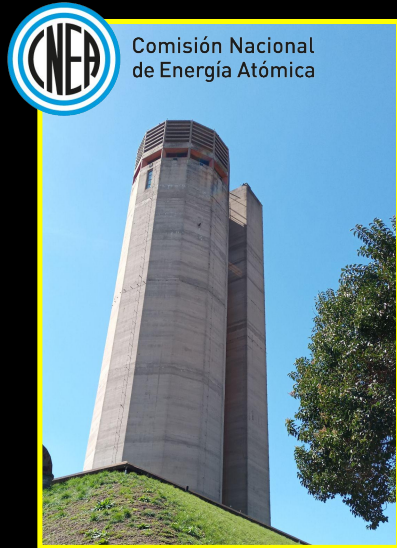
Thank you!


This study was financed, in part, by the São Paulo Research Foundation (FAPESP), Brasil. Process Number #2022/09060-5.

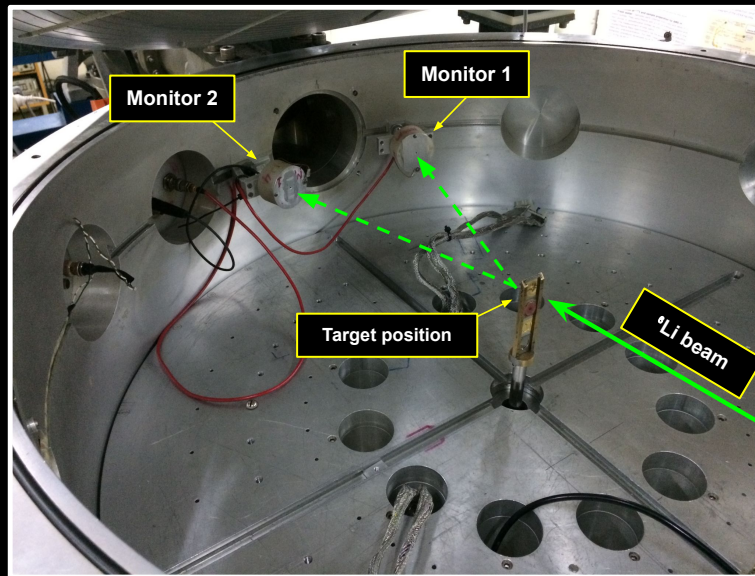
Backup

${}^6\text{Li} + {}^{196}\text{Pt}$ Experimental Setup

Complete fusion and nucleon transfer channel cross sections measured for ${}^6\text{Li} + {}^{196}\text{Pt}$ @ $E_{\text{lab}} = 20, 22, 24, 26, 28, 30, 32, 34$ and 36 MeV $\rightarrow V_{\text{B(Lab)}} = 28.4$ MeV.



 **TANDAR accelerator (Buenos Aires)**
Tandem Van de Graaff — 14 MV

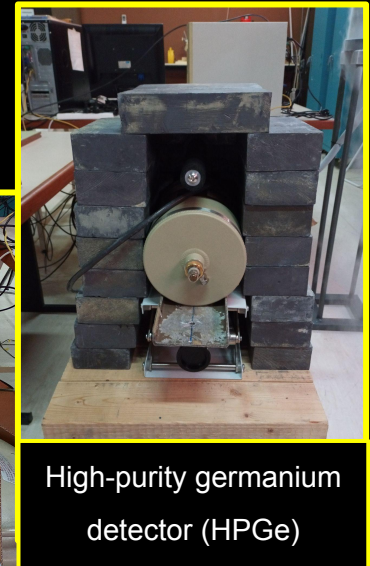
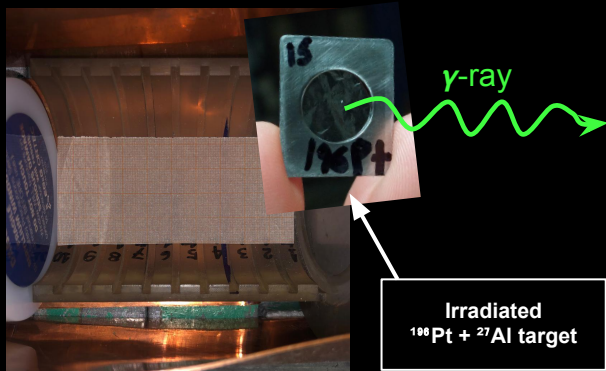


${}^{196}\text{Pt}$ targets with thicknesses between 1 and 2 mg/cm^2

- Produced at LAFNA by rolling
- ${}^{27}\text{Al}$ catcher foils with thicknesses between 250 and $600 \text{ } \mu\text{g/cm}^2$
- Each target irradiated for $\sim 12\text{h}$ (total of ~ 2 weeks).

Experimental Setup — Fusion Product Detection

- Off-line measurements
 - Fusion residues decay by β emission ($T_{1/2} \sim$ minutes to days)
 - After irradiation, targets are placed inside the HPGe detector
 - γ -ray spectra acquired for ~ 24 h per target (~ 1 week for the lowest energy)



Seção de choque de fusão-evaporação

$$\sigma_j = \frac{N_i^{\text{Det}}}{I_i \varepsilon_f(\epsilon)} \frac{d\sigma_{\text{Ruth}}/d\Omega \Omega_{\text{Mon}}}{J(\theta_{\text{Mon}})(e^{-\lambda_i t_2} - e^{-\lambda_i t_f})} \frac{1}{\int_{t_0}^{t_1} e^{\lambda_i t'} N_{\text{Mon}}(t') dt'}$$

$j \rightarrow$ canal (2n, 3n, 4n, transfer, etc)

$i \rightarrow$ raio gamma

N_i^{Det} \rightarrow Área do pico gamma dos espectros

I_i \rightarrow Intensidade relativa do raio gamma

$\varepsilon_f(\epsilon)$ \rightarrow Eficiência do detector em função da energia do raio gamma

Seção de choque de fusão-evaporação

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Seção de choque do espalhamento elástico \rightarrow

$$\frac{d\sigma_{\text{Ruth}}}{d\Omega}(\theta_{\text{Mon}}) = \frac{N_{\text{Mon}}(t) J(\theta_{\text{Mon}})}{\Omega_{\text{Mon}} \frac{\delta N_A}{u} \frac{i(t)}{qe}}$$

N_i^{Det} \rightarrow Área do pico gamma dos espectros

I_i \rightarrow Intensidade relativa do raio gamma

$\varepsilon_f(\epsilon)$ \rightarrow Eficiência do detector em função da energia do raio gamma

Contagens do espalhamento elástico detectado nos monitores no tempo t.

$\delta \rightarrow$ espessura do alvo
 $N_A \rightarrow$ n° eventos / t na direção de θ_{MON}
 $u \rightarrow$ massa atômica do alvo
 $i(t) \rightarrow$ corrente do feixe
 $q \rightarrow$ estado de carga do feixe

Seção de choque de fusão-evaporação

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j → canal (2n, 3n, 4n, transfer, etc)
i → raio gamma

medidas online

Como $T_{1/2}$ é da ordem de horas, foram utilizados intervalos de aquisição de um minuto.

$$\int_{t_0}^{t_1} e^{\lambda_i t'} N_{\text{Mon}}(t') dt' \approx \sum_{k=1}^n e^{\lambda_i t_k} N_{\text{Mon}}(t_k) \Delta t.$$

Tempo de aquisição
em minutos

Seção de choque de fusão-evaporação

$$\sigma_j = \frac{N_i^{\text{Det}}}{I_i \varepsilon_f(\epsilon)} \frac{d\sigma_{\text{Ruth}}/d\Omega \Omega_{\text{Mon}}}{J(\theta_{\text{Mon}}) (e^{-\lambda_i t_2} - e^{-\lambda_i t_f})} \frac{1}{\int_{t_0}^{t_1} e^{\lambda_i t'} N_{\text{Mon}}(t') dt'}$$

$j \rightarrow$ canal (2n, 3n, 4n, transfer, etc)

$i \rightarrow$ raio gamma

medidas *off-line*

λ_i

\rightarrow Constante de decaimento do núcleo

t_2

t_f

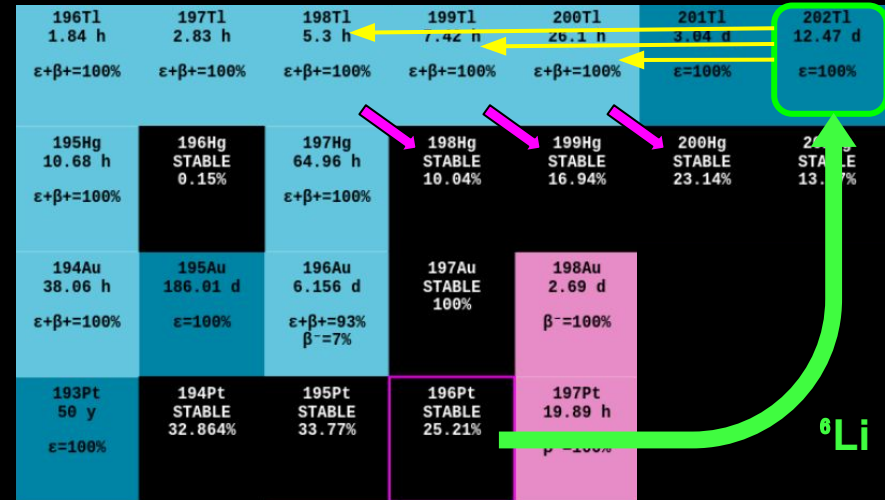
\rightarrow Tempos inicial e final da medição offline

Data Analysis - Preliminary results

- Fusion-evaporation

- ${}^6\text{Li} + {}^{196}\text{Pt} \rightarrow {}^{202}\text{Tl}$ (compound nucleus)*
- Evaporation of 2n, 3n, 4n (5n) neutrons:
 $\rightarrow {}^{200}\text{Tl}, {}^{199}\text{Tl}, {}^{198}\text{Tl}$ (${}^{197}\text{Tl}$)
- These nuclei decay by β^+/ϵ

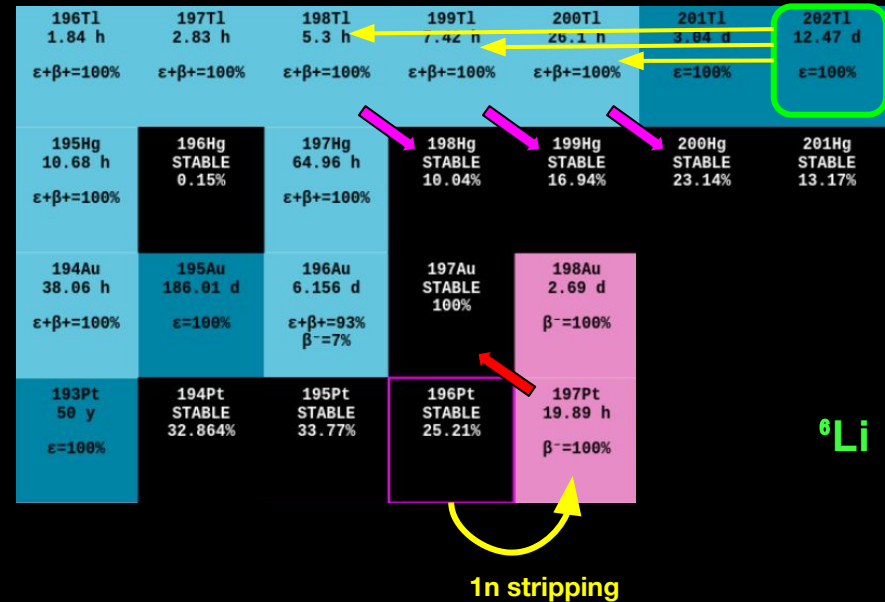
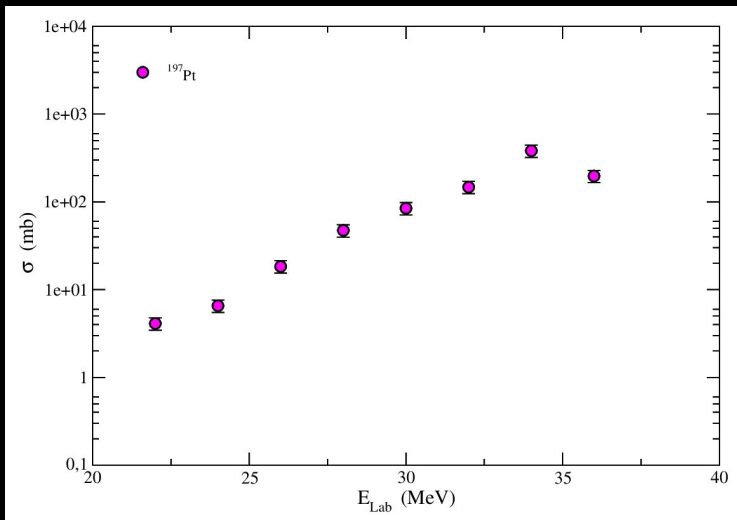
⚠ We detect the γ -rays emitted by the daughter nuclei (Hg isotopes)



Data Analysis - Preliminary results

- Transfer channel

- 1n stripping: $^{197}\text{Pt} (\beta^-) \rightarrow ^{197}\text{Au}$
- 1p pickup under investigation ($^{195}\text{Ir}?$)

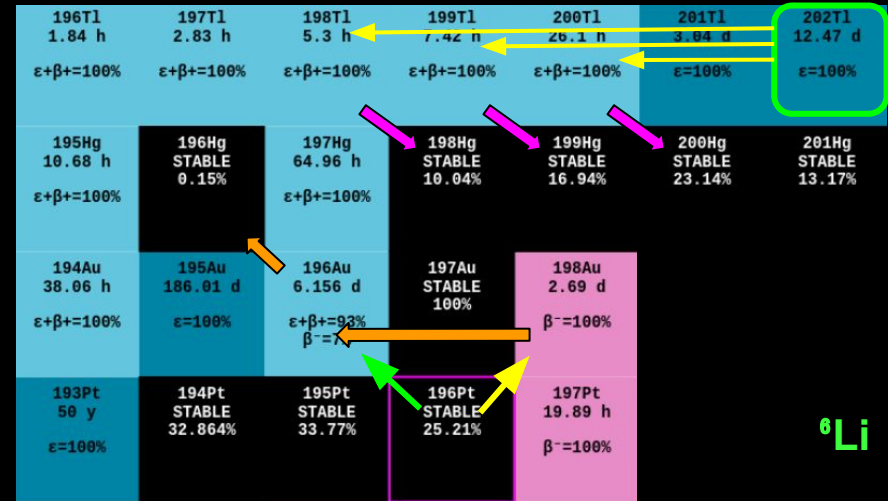


Data Analysis - Preliminary results

- Incomplete Fusion or Charge exchange (?)

^{196}Au can be produced by two competing processes:

- ICF: $d + ^{196}\text{Pt} \rightarrow ^{198}\text{Au}^* \rightarrow ^{196}\text{Au} + 2n$
- Charge exchange: $^6\text{Li} + ^{196}\text{Pt} \rightarrow ^6\text{He} + ^{196}\text{Au}$



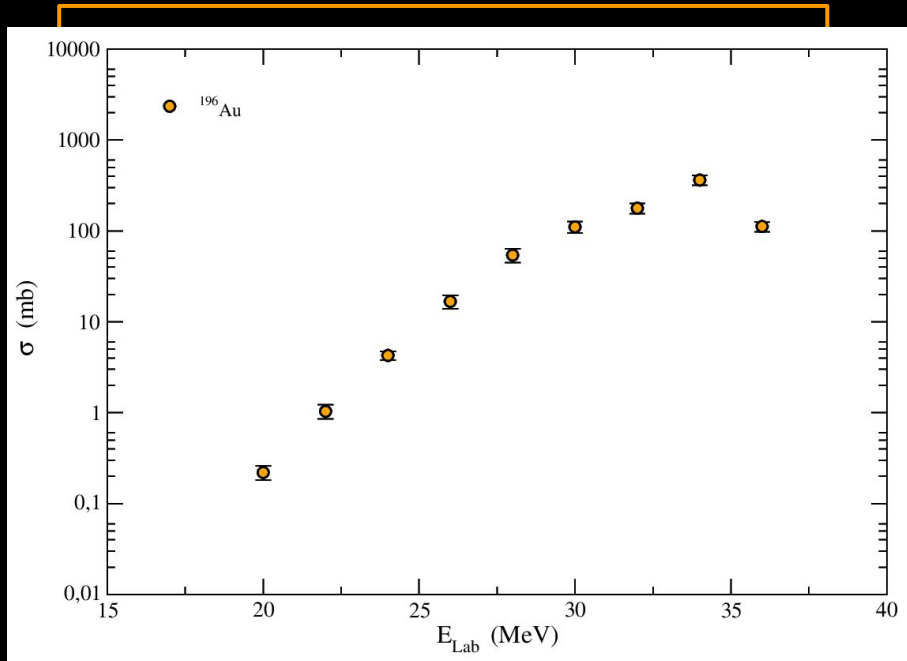
incomplete fusion: $^{196}\text{Pt} + d$

or charge exchange?

^6Li

Data Analysis - Preliminary results

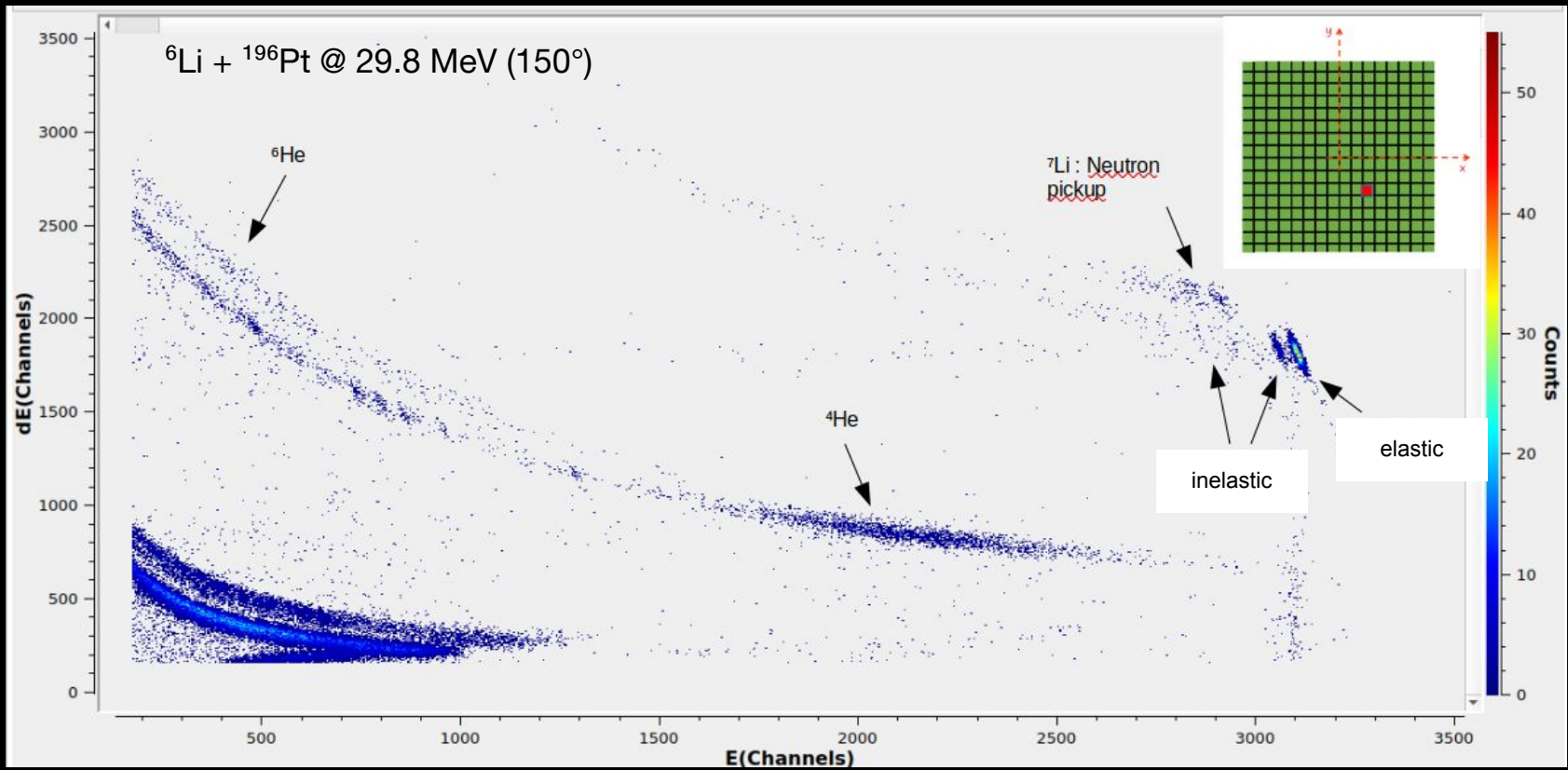
- Incomplete Fusion or Charge exchange (?)



196Tl 1.84 h $\epsilon+\beta+=100\%$	197Tl 2.83 h $\epsilon+\beta+=100\%$	198Tl 5.3 h $\epsilon+\beta+=100\%$	199Tl 7.42 h $\epsilon+\beta+=100\%$	200Tl 26.1 h $\epsilon+\beta+=100\%$	201Tl 3.04 d $\epsilon=100\%$	202Tl 12.47 d $\epsilon=100\%$
195Hg 10.68 h $\epsilon+\beta+=100\%$	196Hg STABLE 0.15%	197Hg 64.96 h $\epsilon+\beta+=100\%$	198Hg STABLE 10.04%	199Hg STABLE 16.94%	200Hg STABLE 23.14%	201Hg STABLE 13.17%
194Au 38.06 h $\epsilon+\beta+=100\%$	195Au 186.01 d $\epsilon=100\%$	196Au 6.156 d $\epsilon+\beta+=93\%$ $\beta^-=7\%$	197Au STABLE 100%	198Au 2.69 d $\beta^-=100\%$		
193Pt 50 y $\epsilon=100\%$	194Pt STABLE 32.864%	195Pt STABLE 33.77%	196Pt STABLE 25.21%	197Pt 19.89 h $\beta^-=100\%$		

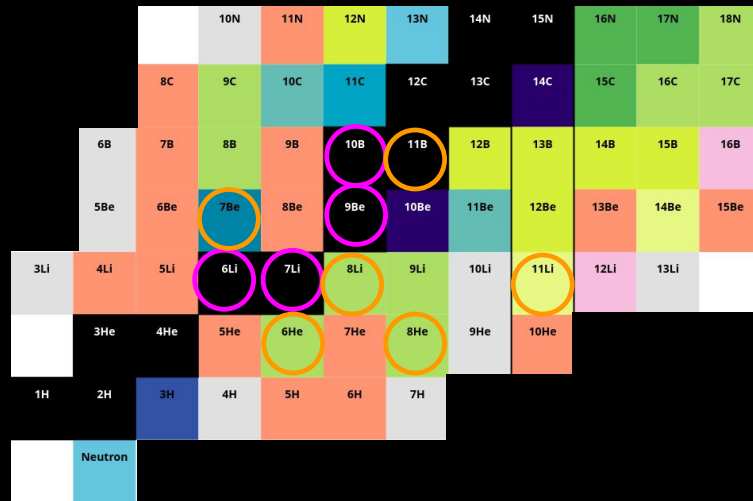
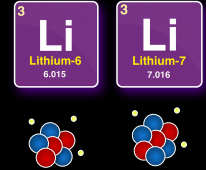
incomplete fusion: $^{196}\text{Pt} + d$
or charge exchange?

^6Li



Introduction

Heavy-ion reactions involving weakly bound stable and unstable nuclei, such as ${}^6, {}^7\text{Li}$, ${}^9\text{Be}$, and ${}^{10}\text{B}$, plays an important role in the study of the properties of radioactive nuclei.



Radioactive nuclei

Nucleus	Cluster	E_B [MeV]
${}^8\text{B}$	${}^7\text{Be} + p$	0.137
${}^6\text{He}$	$\alpha + 2n$	0.973
${}^{11}\text{Li}$	${}^7\text{Li} + 2n$	0.369
${}^{11}\text{Be}$	${}^{10}\text{Be} + n$	0.502

Stable nuclei

Nucleus	Cluster	E_B [MeV]
${}^6\text{Li}$	$\alpha + d$	1.474
${}^7\text{Li}$	$\alpha + t$	2.467
${}^9\text{Be}$	$\alpha + \alpha + n$	1.665
${}^{10}\text{B}$	${}^6\text{Li} + \alpha$	4.46