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# Reaching interesting reactions cross-sections by measuring radioactive recoils with AMS technique: the successful cases of $^{10}\text{Be}$ , $^{14}\text{C}$ and $^{26}\text{Al}$ .

**Luis Acosta**

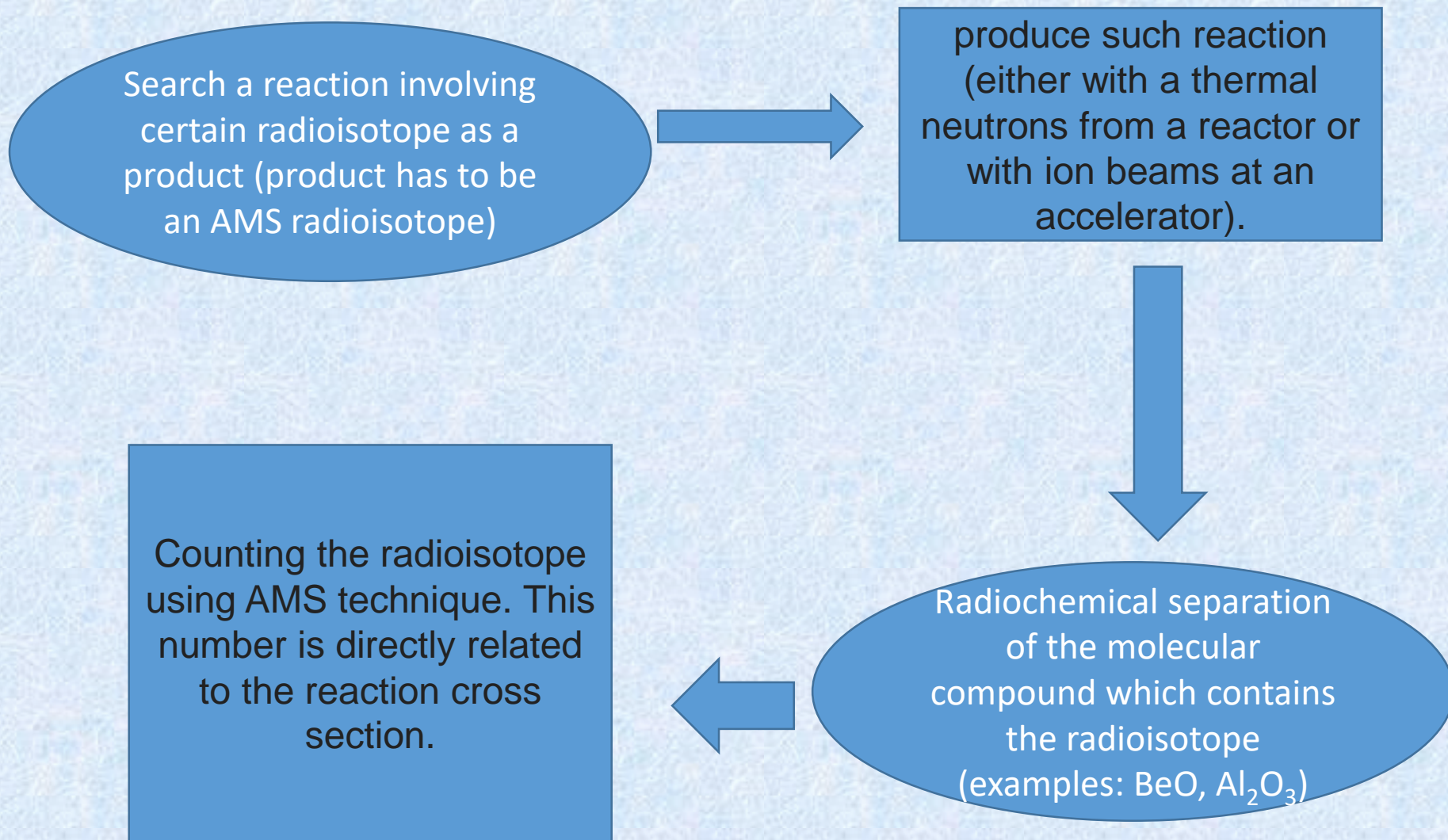
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# Introduction

- Accelerator Mass Spectrometry is a technique commonly used to approach low concentrations of certain long half-life radioisotopes.
- The most important contribution of the technique is the accurate measure of organic sample ages, by separating masses 12,13 and 14 in the case of carbon allocated in such a samples.
- However, the reach of AMS could cover many other scientific scopes, due to it can give us a **precise measure of a very small concentration of a radioisotope**.
- On this direction, AMS can be used to approach reactions of interest for astrophysics, if we spot a specific radioisotope which concentration can be measured with such a technique.
- Starting with this, we have selected specific reactions produced either with low neutrons at a reactor, or positive ions at an accelerator. The chosen reactions are important in astrophysics processes.

# Rough Procedure



# Radioisotope “candidates”

- It is important to choose radioisotopes which could be well measured by using AMS.
  - $^{10}\text{Be}$  ( $1.39 \times 10^6$  years)
  - $^{13}\text{C}$  (stable)
  - $^{14}\text{C}$  (half-life 5730 years)
  - $^{26}\text{Al}$  ( $7.17 \times 10^5$  years)



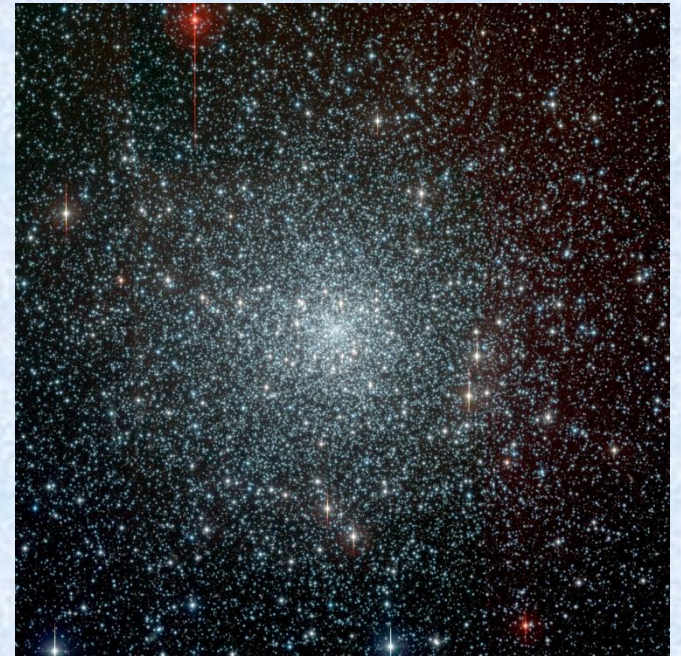
# Which reactions and why?

- Thermal neutron capture reactions, important to understand both stellar and primordial nucleosynthesis:
  - ${}^9\text{Be}(n,\gamma){}^{10}\text{Be}$ 
    - It had been indirectly measured and calculated by different methods, but there is not a general agreement about its precise value.
    - It is needed (beyond models and calculations), to complete the picture of the primordial and star synthesis of light elements.



# Which reactions and why?

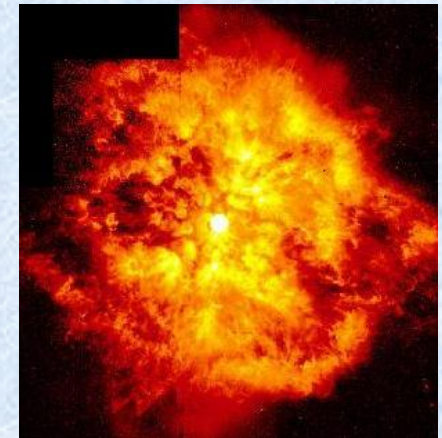
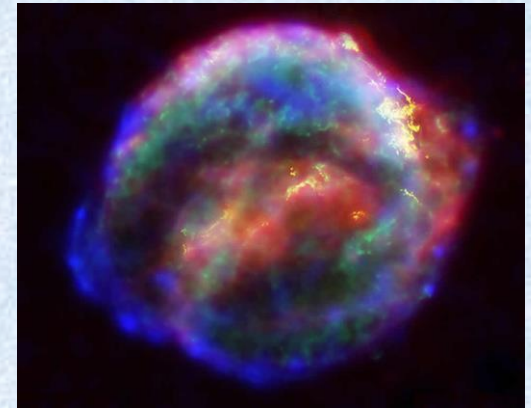
- Thermal neutron capture reactions, important to understand both stellar and primordial nucleosynthesis:
  - $^{14}\text{N}(n,p)^{14}\text{C}$ 
    - It has a capture cross section for thermal neutrons that is very large, so much that it stands as the most important neutron poison in stellar nucleosynthesis.
    - It has been measured with great accuracy and therefore it can be used as a **benchmark** to validate our experimental protocol.
  - $^{13}\text{C}(n,\gamma)^{14}\text{C}$ 
    - importance in the *s process*.





## Which reactions and why?

- Though many studies regarding  $^{26}\text{Al}$  has been carried out, still exist some discrepancies about its production in the interstellar medium.
- $^{28}\text{Si}(\text{d},\alpha)^{26}\text{Al}$ 
  - could contribute to explain the fraction of  $^{26}\text{Mg}$  found in meteorites, considering that not all  $^{26}\text{Mg}$  found, for instance in Allende meteorite, may be related to the previous presence of  $^{26}\text{Al}$ .
- $^{25}\text{Mg}(\text{p},\gamma)^{26}\text{Al}$ 
  - It is not totally known which stars make the most important contribution (W-R, novae, AGB, supernovae explosion, etc.).

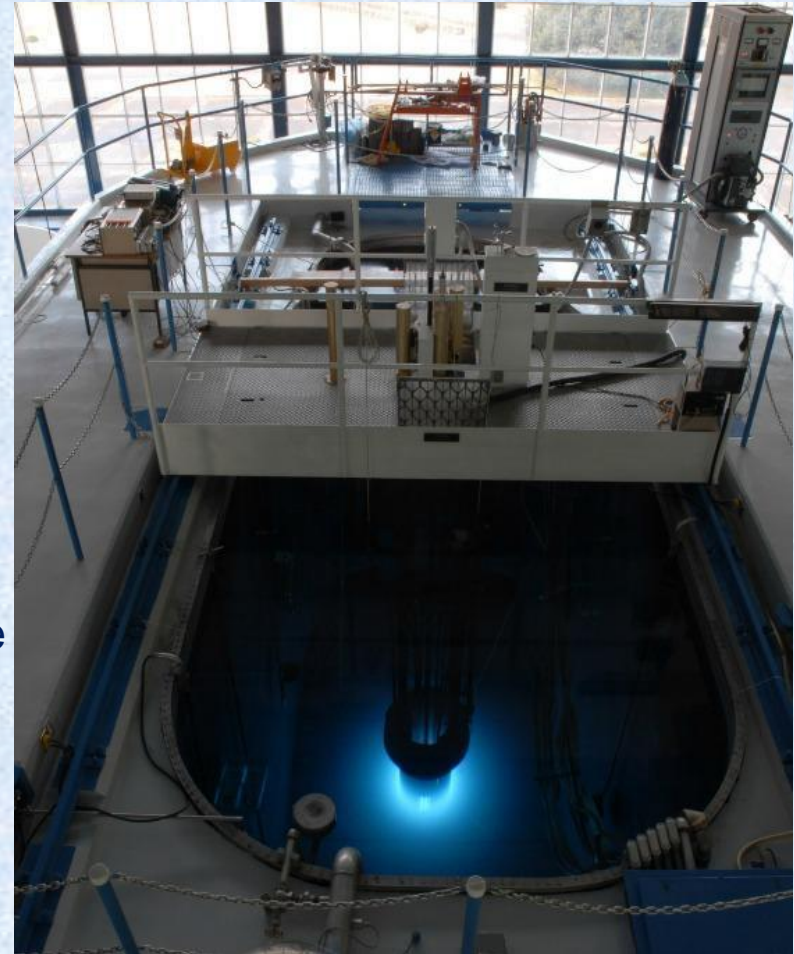


# 1<sup>st</sup> part: Reaction Production



# Neutron capture reactions

- National Institute for Nuclear Research (ININ).
  - The 1 MW TRIGA MARK III reactor is a pool-type research reactor with a movable core, cooled and moderated with light water.
  - Neutrons are moderated with the maximum at 25 meV for a temperature of 290 K; **thermal neutrons**.
  - The structure of the core is a circular arrangement of fuel, control rods, and graphite elements.
  - Thermal neutron fluxes of up to  $3.3 \times 10^{13}$  n/cm<sup>2</sup>s can be reached in stationary mode.



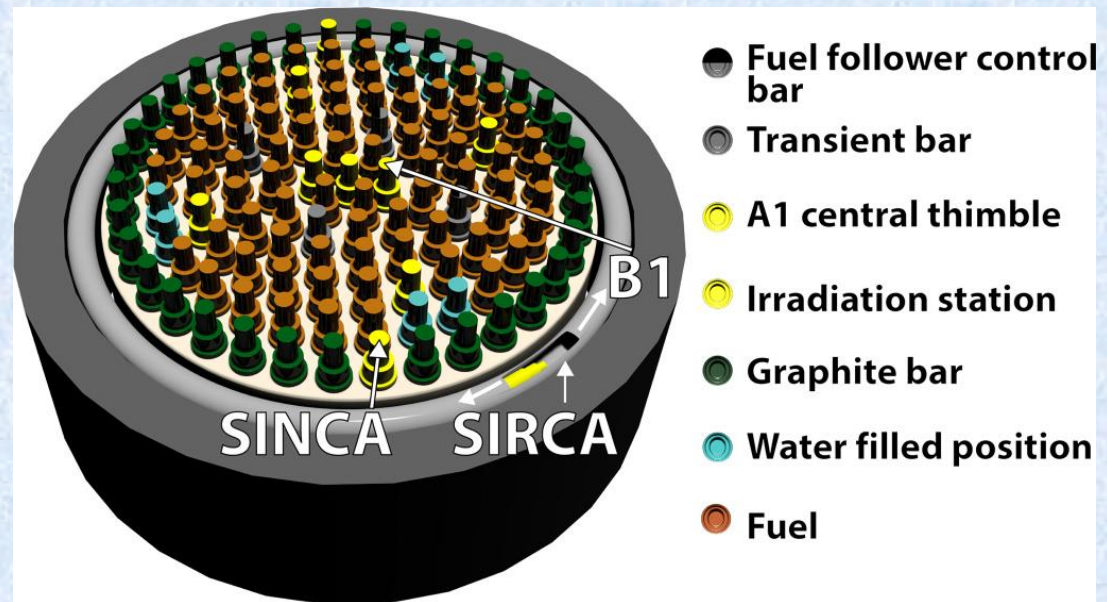
# Targets and irradiation

- **Beryllium oxide.**

- Samples of pure BeO were chemically extracted from 8 ml of Be standard solution [Beryllium ICP Standard Solution,  $\text{Be}_4\text{O}(\text{C}_2\text{H}_3\text{O}_2)_6$ , 1000 mg/l Be Merck], which is currently used as carrier and blank in AMS.

- **Graphite and uracil.**

- For  $^{14}\text{N}(n,p)^{14}\text{C}$  reaction. we used uracil ( $\text{C}_4\text{H}_4\text{N}_2\text{O}_2$ ).
- For the attempt to measure  $^{13}\text{C}(n,\gamma)^{14}\text{C}$  reaction cross section, we used natural graphite (98.9% of  $^{12}\text{C}$  and 1.1% of  $^{13}\text{C}$ ).



- **BeO.** SIRCA port: neutron flux of  $2.26 \times 10^{11}$  n/cm<sup>2</sup>s (30 min/sample and 120 min/sample).
- **Uracil.** SINCA port: neutron flux of  $4.42 \times 10^{12}$  n/cm<sup>2</sup>s (20 s/sample) .
- **Graphite.** B1 port. neutron flux of  $2.3 \times 10^{13}$  n/cm<sup>2</sup>s (10 h/sample and 2 h/sample (Cd container)).



# $^{28}\text{Si}(d,\alpha)^{26}\text{Al}$ reaction.

- Two measurements using two different facilities:
  - Van der Graaff 5.5 MV, (Lab. CGF @ IFUNAM, Mexico City)
  - CN-Tandem 6 MV, (ININ, Ocoyoacac Edo. Mex.).
  - Both facilities can produce deuterium beams of (1-2 MeV 1 - 4 MeV, respectively  $\sim 1 \mu\text{A}$ )

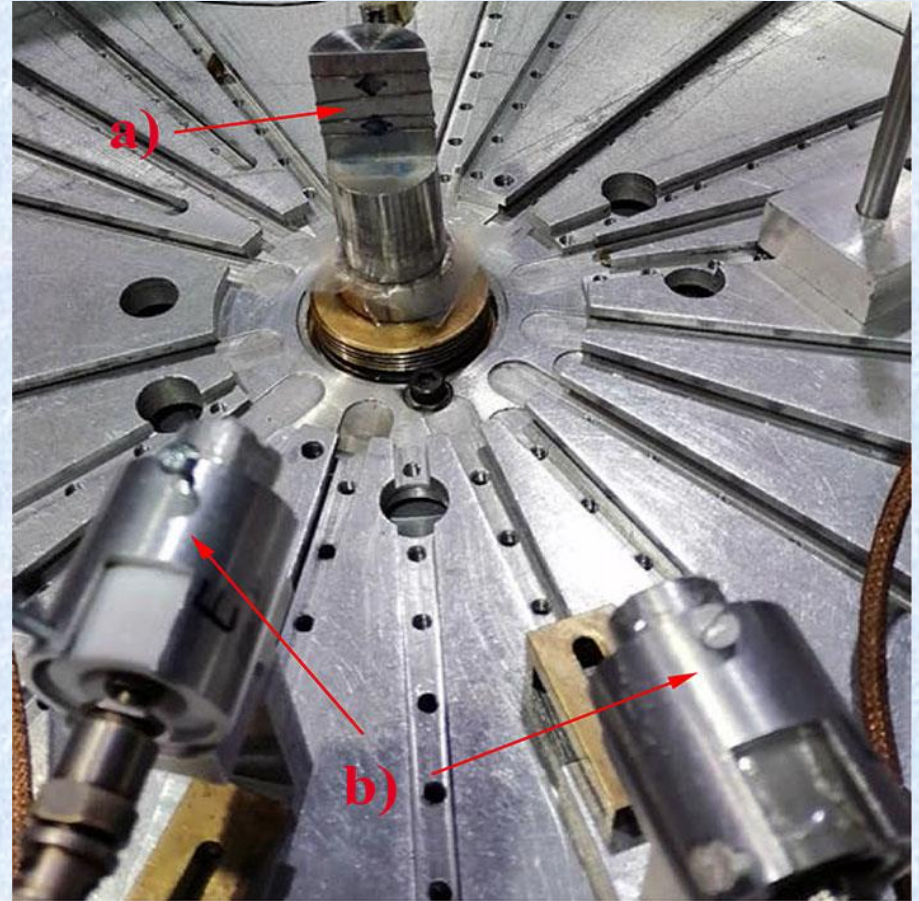




# $^{28}\text{Si}(\text{d},\alpha)^{26}\text{Al}$ reaction experimental setup



- Silicon wafers were chosen as targets:
  - wide enough to allow proper alignment with the beam, which is 2 mm diameter,
  - thick enough to stop the beam and
  - small enough to facilitate the digestion in the radio-chemistry laboratory Chemical separation of Al from Si targets tested before the experiment (attaining finally  $\text{Al}_2\text{O}_3$ ).



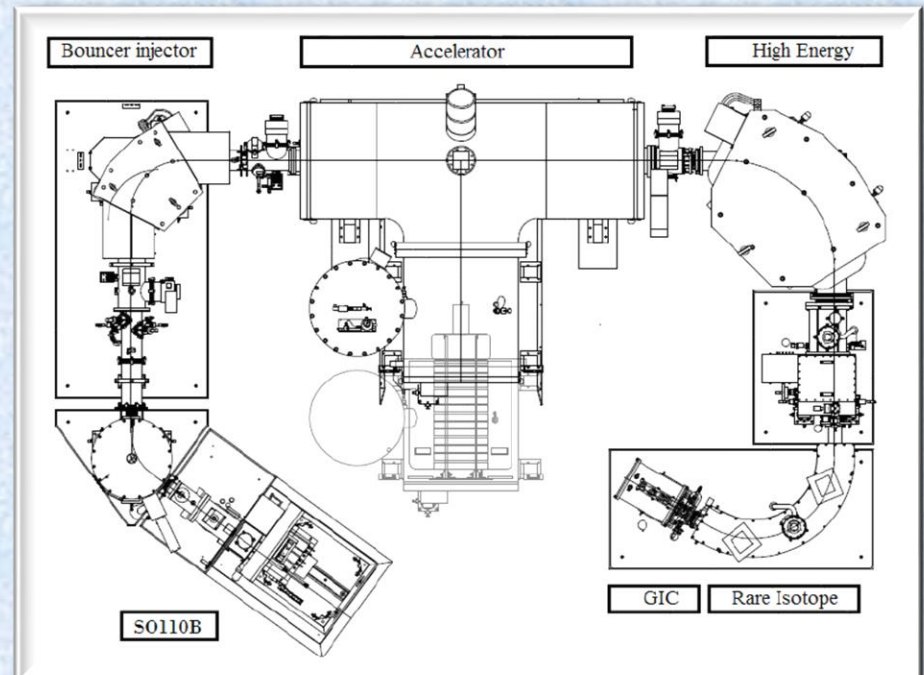
- a) New target-holder and Si waffles.
- b) Silicon detectors (500  $\mu\text{m}$  thickness)

# 2<sup>nd</sup> part: AMS measurement



# The LEMA facility.

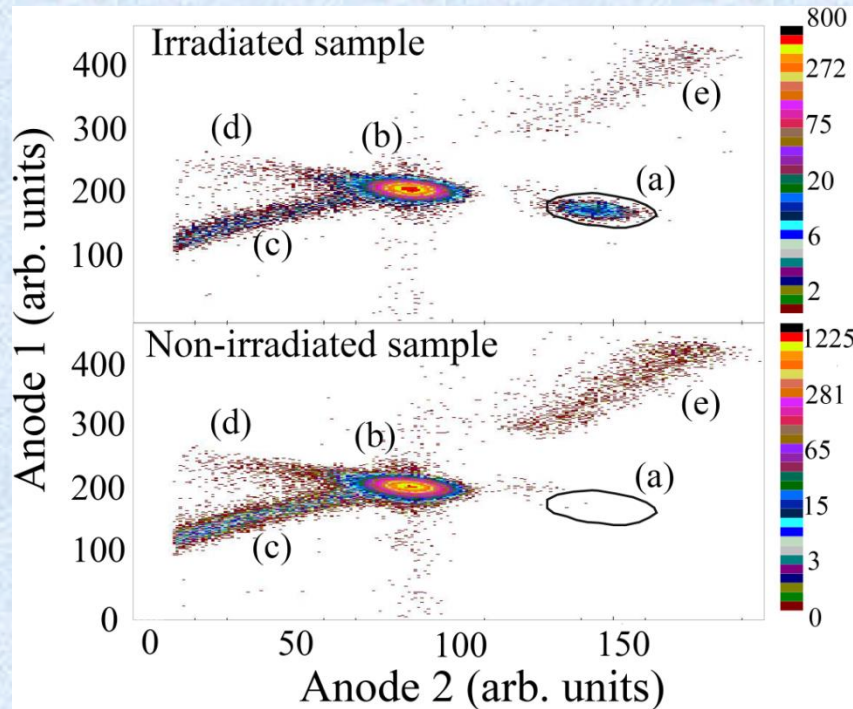
- The National Laboratory of Accelerator Mass Spectrometry (LEMA-IFUNAM) was commissioned in 2013.
- A tandetron of 1 MV (HVEE) equipped with peripheral laboratories:
  - for the cleaning and chemical samples preparation;
  - Graphitization of carbon samples.
- Sequential injection makes possible the measurement of isotopes present in concentration ratios from  $10^{-10}$  to  $10^{-15}$ .
- LEMA was calibrated to measured concentrations of  $^{10}\text{Be}$ ,  $^{14}\text{C}$ ,  $^{26}\text{Al}$ ,  $^{129}\text{I}$  and Pu isotopes.





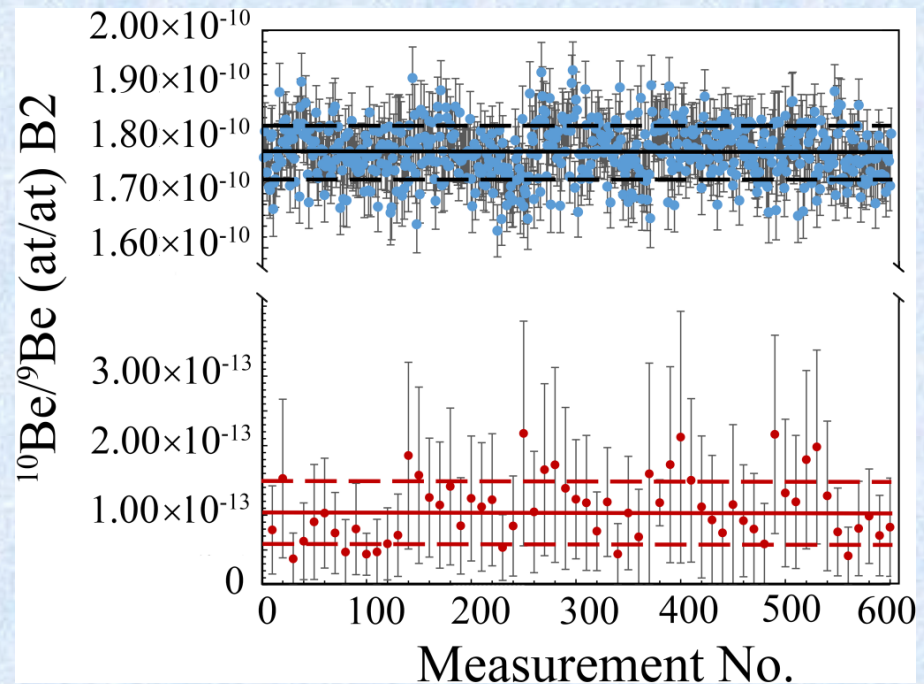
# Results for neutron capture reactions.

## BeO samples.



$\Delta E$ -E spectra from gas detector of LEMA system.

Events enclosed in black polygon are  $^{10}\text{Be}$  counts.

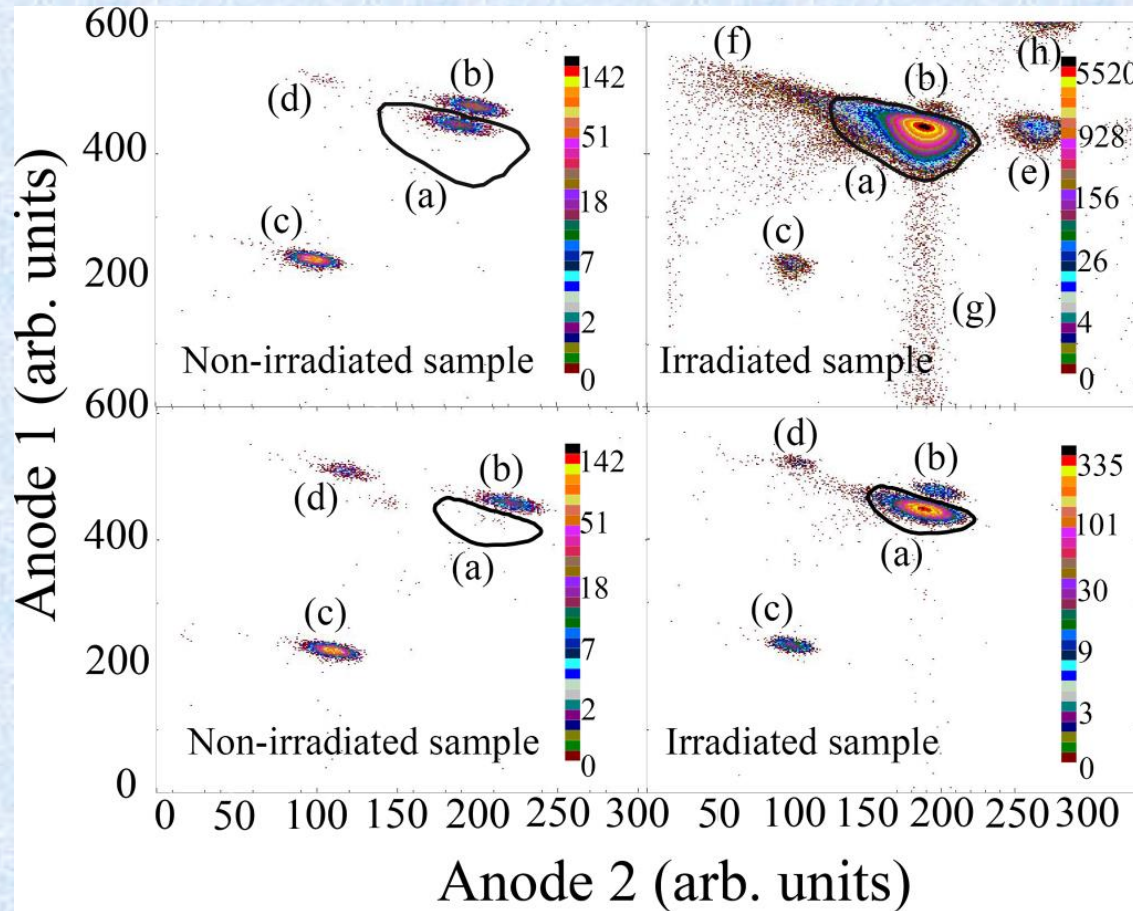


Data from irradiated (blue dots) and non-irradiated (red dots, averaged over ten values) samples.

The continuous and dashed lines show the average and the standard deviation, respectively.

# Results for neutron capture reactions.

## Graphite and uracil samples.



← Graphite

← Uracil

$\Delta E$ -E spectra from gas detector of LEMA system.  
Events enclosed in black polygon are  $^{14}\text{C}$  counts.

# Reaction cross sections

Reaction	$\sigma_{\text{LEMA}} [\text{b}]$	$\sigma_{\text{NIST}} [\text{b}]$	$\sigma_{\text{IAEA}} [\text{b}]$	$\sigma_{\text{ANR}} [\text{b}]$
$^{14}\text{N}(\text{n},\text{p})^{14}\text{C}$	$2.07 \pm 0.37$	1.91	-	$1.86 \pm 0.03$
$^{13}\text{C}(\text{n},\gamma)^{14}\text{C}$	$0.18 \pm 0.03$	$0.00137 \pm 0.00004$	-	$0.00137 \pm 0.00004$
$^9\text{Be}(\text{n},\gamma)^{10}\text{Be}$	<b><math>0.0097 \pm 0.0005</math></b>	$0.0076 \pm 0.0008$	0.0087	-

- Cross section found for  $^{14}\text{N}(\text{n},\text{p})^{14}\text{C}$  reaction is in agreement with the previous measured values.
- Cross section found for  $^{13}\text{C}(\text{n},\gamma)^{14}\text{C}$  it is far from the values reported in the literature. The discrepancy could be related to the production of  $^{14}\text{C}$  by neutron reactions in Nitrogen, which is part of the sample and no simple to quantify.
- **Cross section found for  $^9\text{Be}(\text{n},\gamma)^{10}\text{Be}$  is the first direct measurement reported. It is in good agreement with the indirect measurements previously reported.**

PHYSICAL REVIEW C **102**, 044601 (2020)

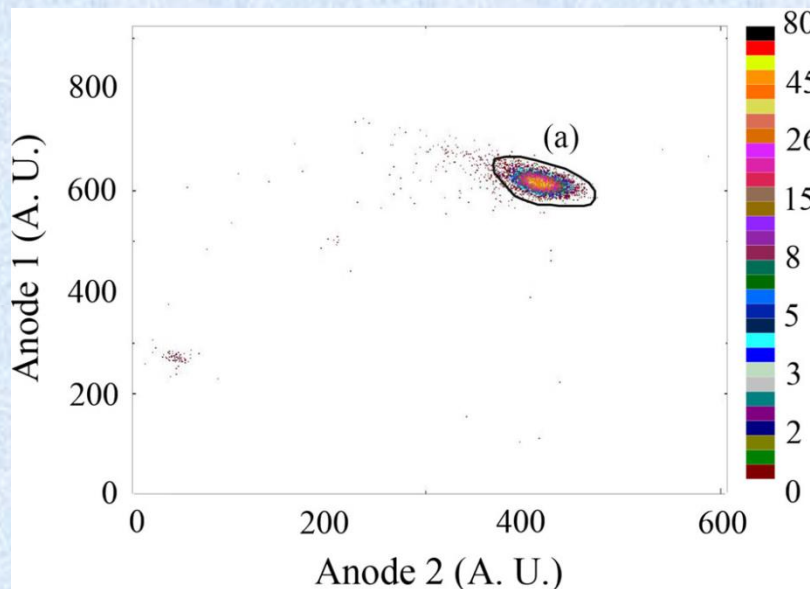
**Measurement of the thermal neutron capture cross section by  $^9\text{Be}$  using the neutron flux from a nuclear research reactor and the AMS technique**

D. J. Marín-Lámbarri<sup>1,\*</sup>, J. García-Ramírez<sup>1</sup>, E. Sánchez-Zúñiga<sup>1</sup>, S. Padilla<sup>1</sup>, L. Acosta<sup>1</sup>, E. Chávez<sup>1</sup>,  
H. S. Cruz-Galindo<sup>2</sup>, A. Huerta<sup>1</sup>, G. Méndez<sup>1,3</sup>, R. Raya-Arredondo<sup>2</sup>, M. Rodríguez-Ceja<sup>1,4</sup>,  
C. Solís<sup>1</sup> and L. Barrón-Palos<sup>1</sup>



# $^{28}\text{Si}(d,\alpha)^{26}\text{Al}$ results.

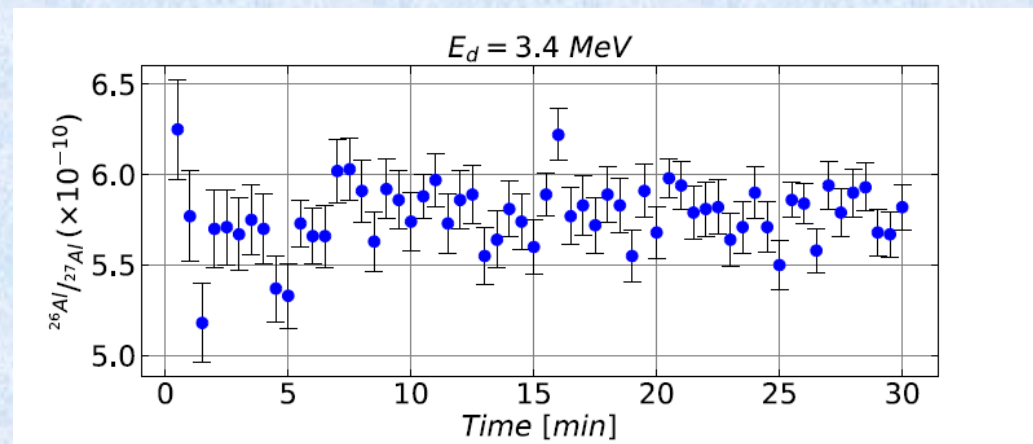
## $\text{Al}_2\text{O}_3$ samples



$\Delta E$ -E spectra from gas detector of LEMA system.

Events enclosed in black polygon are  $^{26}\text{Al}$  counts.

Still necessary improves the precision in the measurement of deuterium flux.



Data from irradiated samples.

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<https://doi.org/10.1140/epjp/s13360-020-00906-7>

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Regular Article



AMS cross-section measurement for the  $^{28}\text{Si}(d,\alpha)^{26}\text{Al}$  reaction near the Coulomb barrier

G. Reza<sup>1,a</sup>, A. B. Zunun-Torres<sup>1</sup>, S. Padilla<sup>1</sup>, J. Mas-Ruiz<sup>1</sup>, D. J. Marín-Lámbarri<sup>1</sup>, L. Acosta<sup>1</sup>, P. Amador-Valenzuela<sup>2</sup>, E. Andrade<sup>1</sup>, D. Belmont<sup>1</sup>, L. E. Charón<sup>1</sup>, A. Huerta<sup>1</sup>, D. Godos-Valencia<sup>1</sup>, J. N. Martínez<sup>3</sup>, C. G. Méndez<sup>1</sup>, E. Moreno<sup>2</sup>, G. Murillo<sup>2</sup>, R. Policroniades<sup>2</sup>, M. Rodríguez-Ceja<sup>1</sup>, S. Sandoval-Hipólito<sup>1</sup>, V. R. Sharma<sup>2</sup>, C. Solís<sup>1</sup>, A. Varela<sup>2</sup>, P. Villaseñor<sup>2</sup>, E. Chávez<sup>1</sup>

# Summary and conclusions

- The combination of reaction production + AMS technique was probed, founding a good alternative **for the direct measurement of interesting cross section**.
- Thermal neutrons produced from a small reactor as well as low energy beams from small accelerators (ININ and IFUNAM machines) are good options to produce the reactions.
- Radioisotope concentrations can later be measured using an AMS system (as LEMA).
- Neutron capture reactions for Beryllium and Nitrogen targets (for the  $^{14}\text{C}$  and  $^{10}\text{B}$  production respectively) were well measured, showing the effectiveness of the method.
- Particularly for  **$^9\text{Be}(n,\gamma)^{10}\text{Be}$  reaction**, we achieve the first direct measurement of the total cross section, which agrees with previous indirect measurements.
- **$(d,\alpha)^{26}\text{Al}$  was also studied**, founding promising results for a further measurement of the total cross section in a wide low energy range.
- Thank to the new LEMA beam-line, these studies will be able to extend to other reactions as the  $(p,\gamma)^{26}\text{Al}$  at 400 keV, which is crucial for the understanding of the  $^{26}\text{Al}$  production on stellar nucleosynthesis.

# Thank you for your attention



## Collaboration:

L. Acosta, D. J. Marín-Lámbarri , J. García-Ramírez , E. Sánchez-Zúñiga, S. Padilla, E. Chávez , H. S. Cruz-Galindo , A. Huerta, G. Méndez, R. Raya-Arredondo, M. Rodríguez-Ceja, C. Solís, L. Barrón-Palos, G. Reza, A. B. Zunun-Torres, J. Mas-Ruiz, P. Amador-Valenzuela, E. Andrade, D. Belmont, L. E. Charón, D. Godos-Valencia, J. N. Martínez, E. Moreno, G. Murillo, R. Policroniades, S. Sandoval-Hipólito, V. R. Sharma, A. Varela, P. Villaseñor and V. Araujo-Escalona.

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GRANTS: CONACYT 271802, 280760, 299073, 299186, 294537 and DGAPA-UNAM IN107820, IN109120 , AG101120, IG100619 and IG101016.

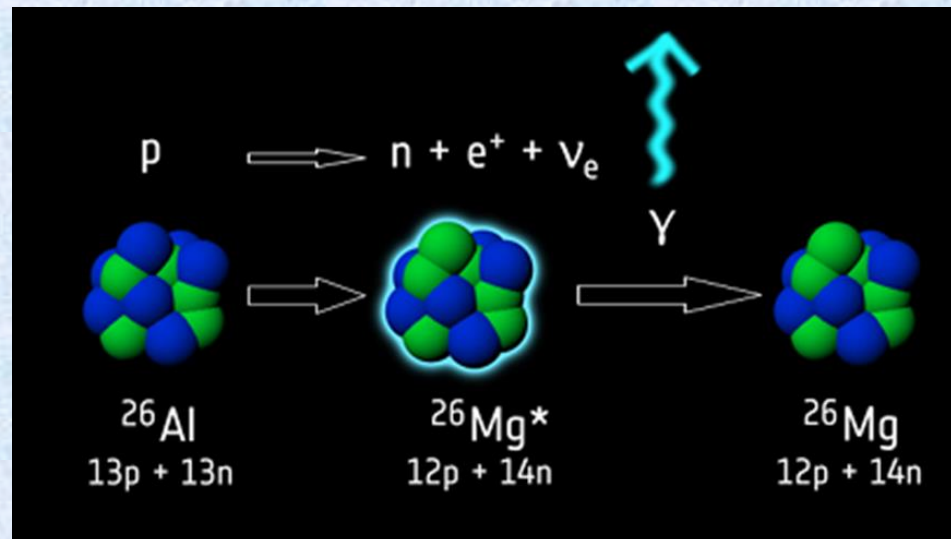






# Which reactions and why?

- The  $^{26}\text{Al}$  is a long-live radioisotope ( $T_{1/2} = 0.716 \text{ Ma}$ ).
- Its  $\gamma$ -decay ( $E_\gamma = 1.809 \text{ MeV}$ ) is transparent in the interstellar medium, allowing to be measured and gives evidence of presently active nucleosynthesis.
  - The measure of this decay allows to quantify the  $^{26}\text{Al}$  production in the space, giving a good contribution to the existing nucleosynthesis models.

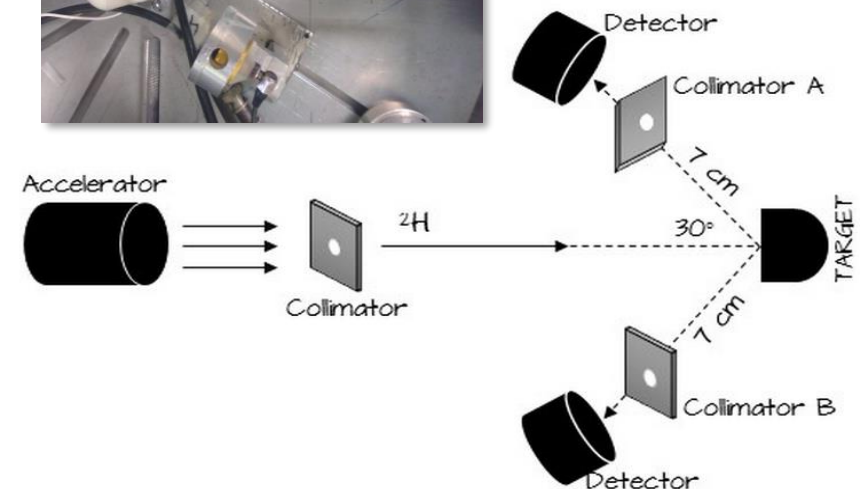
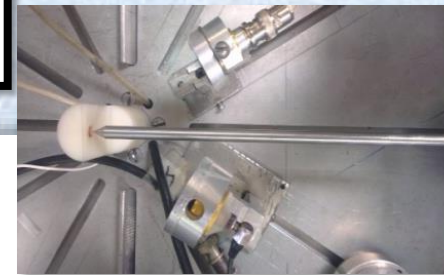
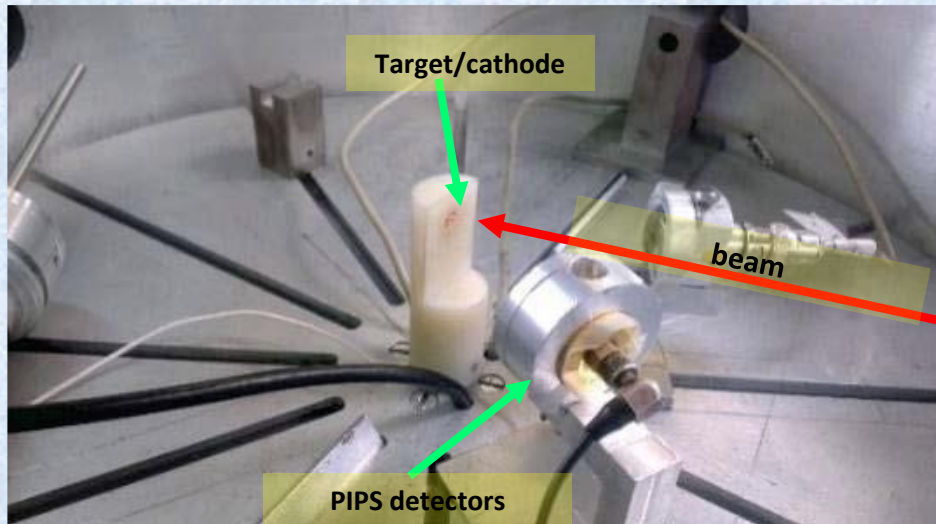
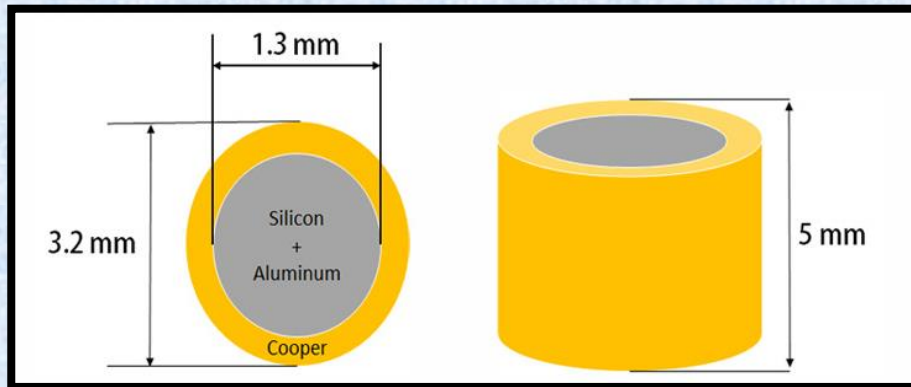




# First attempt to measure $^{28}\text{Si}(d,\alpha)^{26}\text{Al}$ reaction

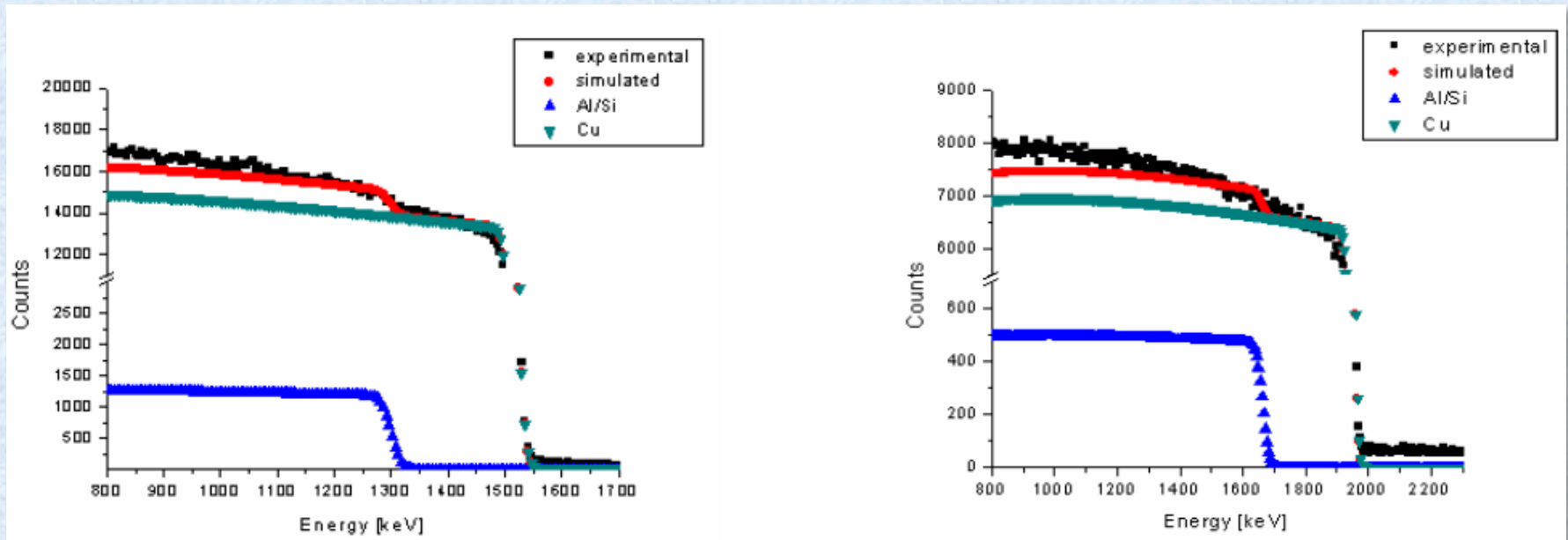


- Using a combination of 50-50 Si/Al (3 mg Al + 3 mg Si) compressed inside a cathode for AMS system.



# First attempt to measure $^{28}\text{Si}(d,\alpha)^{26}\text{Al}$ reaction

- However, due to the small size of the sample, most of the beam (till 80%) was impinging the cooper container (cathode).
- The consequences were  $^{26}\text{Al}$  cross section of  $3.9(4) \mu\text{b}$  (1.1 MeV),  $1.5(2) \mu\text{b}$  (1.5 MeV) and  $1.3(1) \mu\text{b}$  (1.8 MeV).

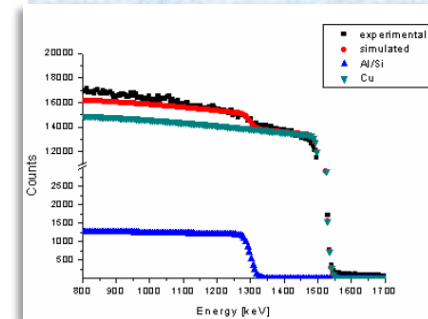
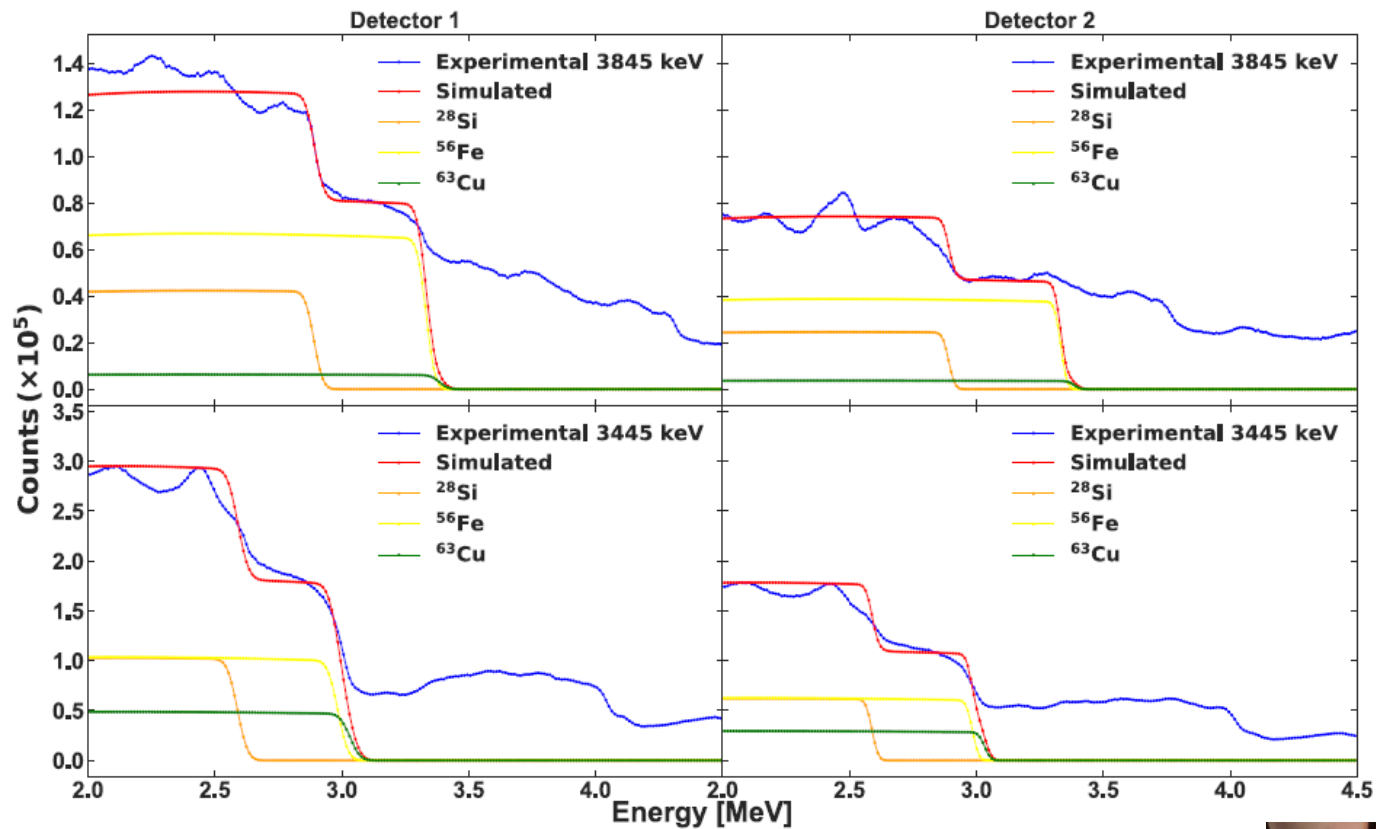


V. Araujo-Escalona, et. al., J. Phys. CS 730, 012003 (2016)

V. Araujo-Escalona, et. al., Phys. Procedia 90, 421–428 (2017)

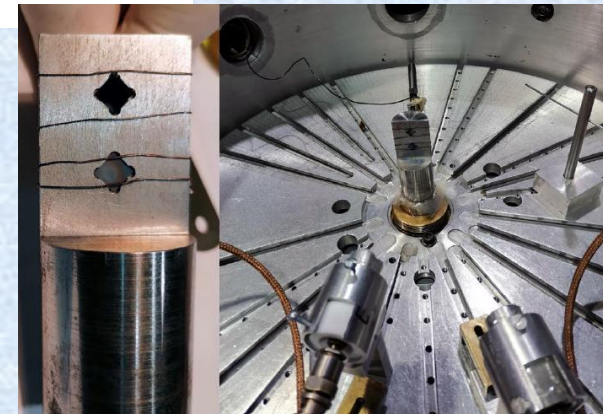
L. Acosta et al., Eur. Phys. J. W. C 165, 01001 (2017)

# $^{28}\text{Si}(d,\alpha)^{26}\text{Al}$ results.



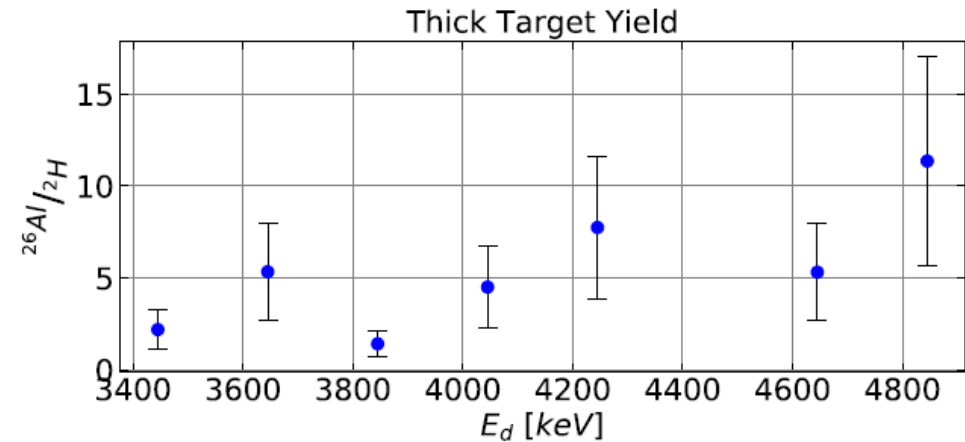
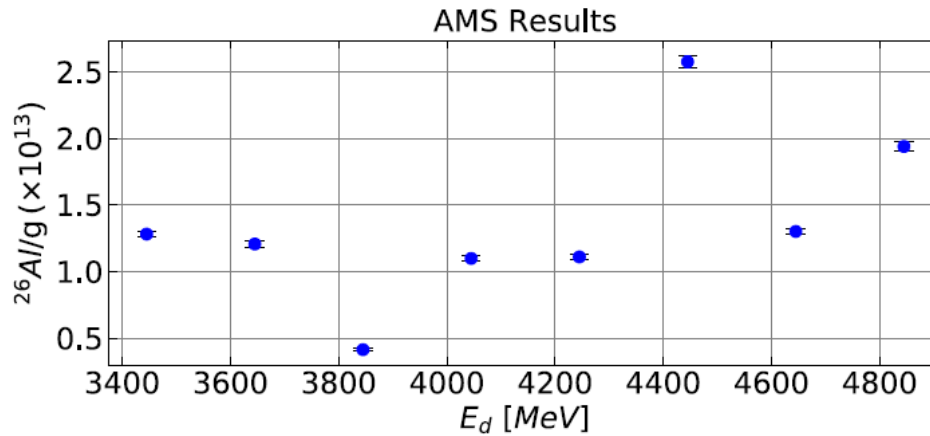
RBS analysis of deuterons scattered at  $165^\circ$  by Si target and other elements.

For this 2<sup>nd</sup> attempt, the beam on Si target for all the measured energies was  $\sim 70\%$  (most of the beam was on Si).





# Measure of the $^{26}\text{Al}$ concentrations



- $^{26}\text{Al}$  concentrations can be well measured with AMS. The uncertainties grows noticeably when  $^{26}\text{Al}$  events are normalized with the thick target.
- Larger uncertainties may come from the poor determination of the deuteron flux.

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<https://doi.org/10.1140/epjp/s13360-020-00906-7>

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## AMS cross-section measurement for the $^{28}\text{Si}(d,\alpha)^{26}\text{Al}$ reaction near the Coulomb barrier

G. Reza<sup>1,a</sup>, A. B. Zunun-Torres<sup>1</sup>, S. Padilla<sup>1</sup>, J. Mas-Ruiz<sup>1</sup>, D. J. Marín-Lámbarri<sup>1</sup>, L. Acosta<sup>1</sup>, P. Amador-Valenzuela<sup>2</sup>, E. Andrade<sup>1</sup>, D. Belmont<sup>1</sup>, L. E. Charón<sup>1</sup>, A. Huerta<sup>1</sup>, D. Godos-Valencia<sup>1</sup>, J. N. Martínez<sup>3</sup>, C. G. Méndez<sup>1</sup>, E. Moreno<sup>2</sup>, G. Murillo<sup>2</sup>, R. Policroniades<sup>2</sup>, M. Rodríguez-Ceja<sup>1</sup>, S. Sandoval-Hipólito<sup>1</sup>, V. R. Sharma<sup>2</sup>, C. Solís<sup>1</sup>, A. Varela<sup>2</sup>, P. Villaseñor<sup>2</sup>, E. Chávez<sup>1</sup>

# Improvements and further $^{26}\text{Al}$ measurements.

- To achieve the total cross section for  $(d,\alpha)$  reaction:
  - a tighter collimation of the deuteron beams to have a more robust determination of the beam spot on target,
  - particle identification using a telescope ( $\Delta E$ - $E$ ) of the back-scattered particles detected,
  - add a very thin (20 nm) gold layer to the silicon slabs to monitor on the elastic scattering on gold and not on silicon.
- The  $(p,\gamma)$  reaction at 400 keV (in the new **LEMA beam-line** is the next to measure. Natural Mg targets are under chemical test.

