The AMS technique as an important tool for the measurement of astrophysical cross sections.

Luis Acosta

Instituto de Física

Universidad Nacional Autóma de México

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 an 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

Search a reaction involving certain radioisotope as a product (product has to be an AMS radioisotope)

produce such reaction (either with a thermal neutrons from a reactor or with ion beams at an accelerator).

Radiochemical separation of the molecular compound which contains the radioisotope (examples: BeO, Al_2O_3)

Counting the radioisotope using AMS technique. This number is directly related to the reaction cross section.

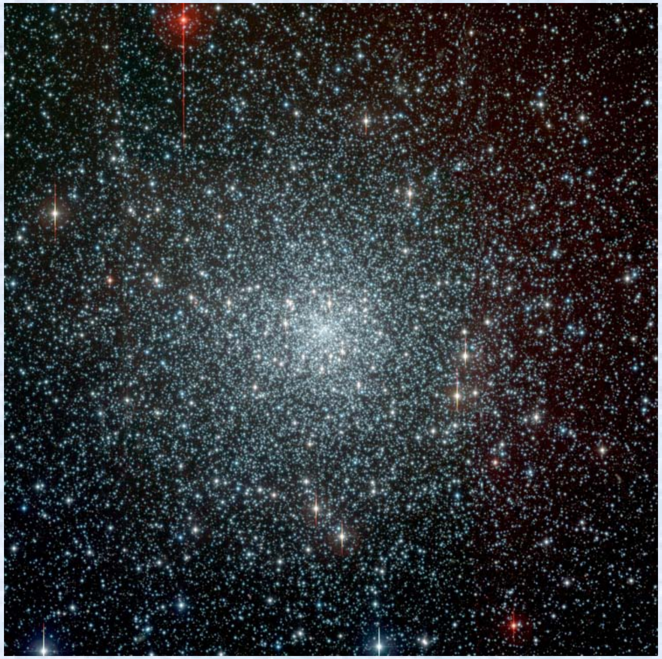
Radioisotope “candidates”

- It is important to choose radioisotopes which could be well measured by using AMS.

  - ^{10}Be (1.39×10^{6} years)
  - ^{13}C (stable)
  - ^{14}C (half-life 5730 years)
  - ^{26}Al (7.17×10^{5} years)

Which reactions and why?

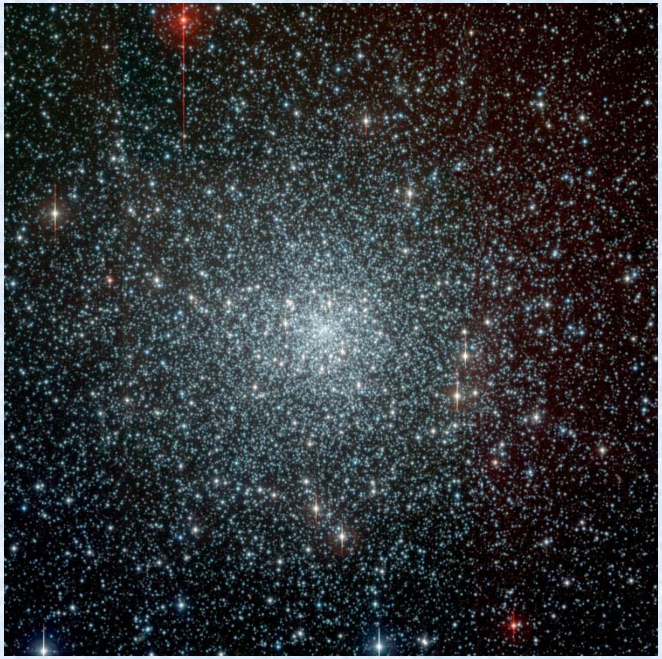
- Thermal neutron capture reactions, important to understand both stellar and primordial nucleosynthesis:



  - $^{9}Be(n,\gamma)^{10}Be$
    - 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:

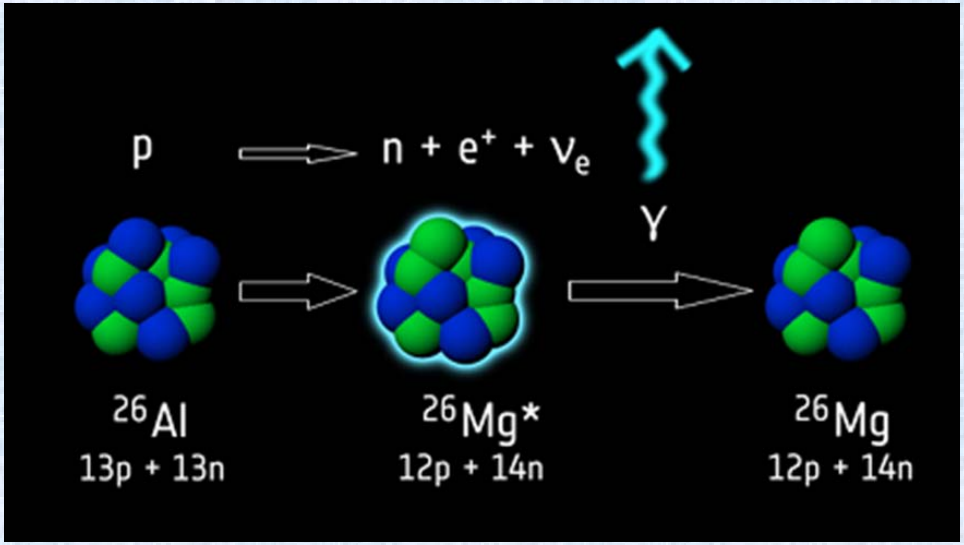


  - $^{14}N(n,p)^{14}C$
    - It has a capture cross section for thermal neutrons that is very large, so much that it stands as the most important neutron poison in stellar nucleosynthesis.
    - It has been measured with great accuracy and therefore it can be used as a benchmark to validate our experimental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

  - $^{13}C(n,\gamma)^{14}C$
    - importance in the *s process.*

Which reactions and why?

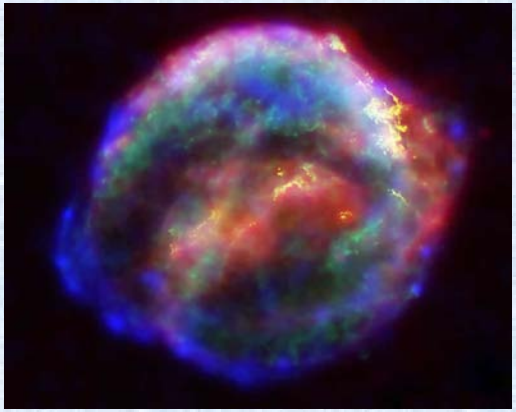
- The ^{26}Al is a long-live radioisotope ($T_{1/2}$ = 0.716 Ma).
- Its γ-decay (E_γ=1.809 MeV) is transparent in the interstellar medium, allowing to be measured and gives evidence of presently active nucleosynthesis.
  - The measure of this decay allows to quantify the ^{26}Al production in the space,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

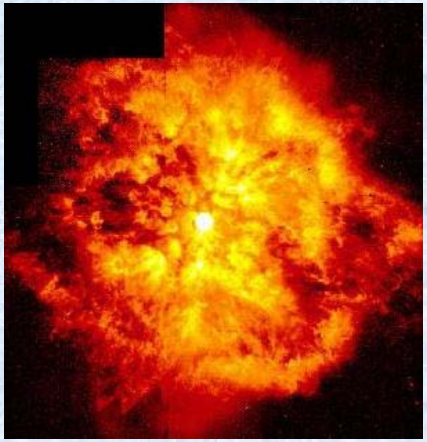


Which reactions and why?

- Though many studies regarding ^{26}Al has been carried out, still exist some discrepancies about its production in the interstellar medium.

  - **$^{28}Si(d,\alpha)^{26}Al$**
    - could contribute to explain the fraction of ^{26}Mg found in meteorites, considering that not all ^{26}Mg found, for instance in Allende meteorite, may be related to the previous presence of ^{26}Al.
  - $^{25}Mg(p,\gamma)^{26}Al$
    - It is not totally known which starts make the most important contribution (W-R, novae, AGB, supernovae explosion, etc.).





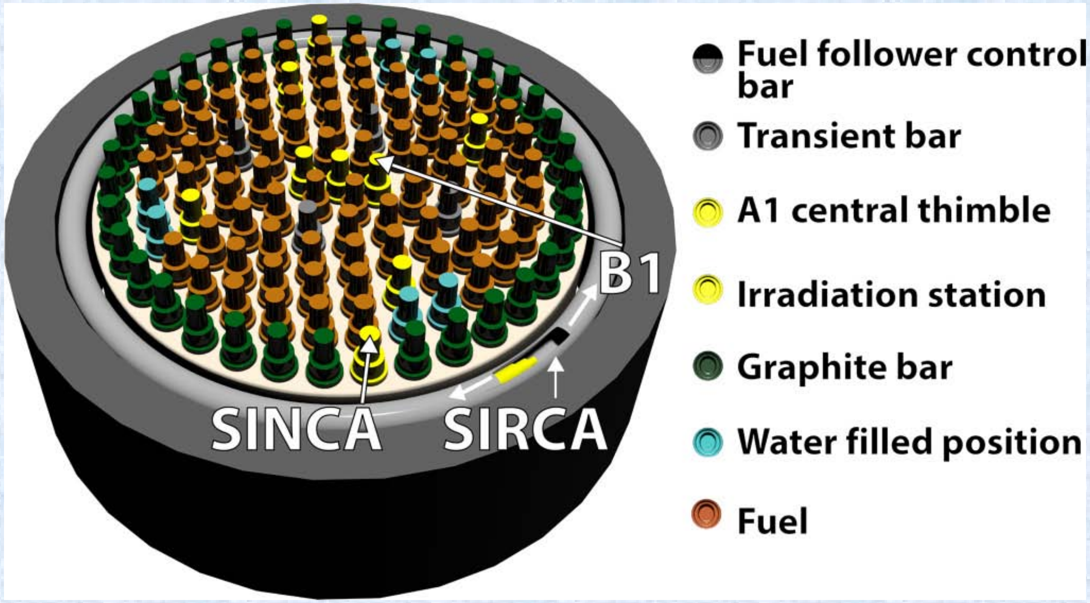
1st part: Reaction Production

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 3.3×10^{-13} n/cm^2s 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, $Be_4O(C_2H_3O_2)_6$, 1000 mg/l Be Merck],which is currently used as carrier and blank in AMS.



- Graphite and uracil.
  - For $^{14}N(n,p)^{14}C$ reaction. we used uracil ($C_4H_4N_2O_2$).
  - For the attempt to measure $^{13}C(n,\gamma)^{14}C$ reaction cross section, we used natural graphite (98.9% of ^{12}C and 1.1% of ^{13}C).

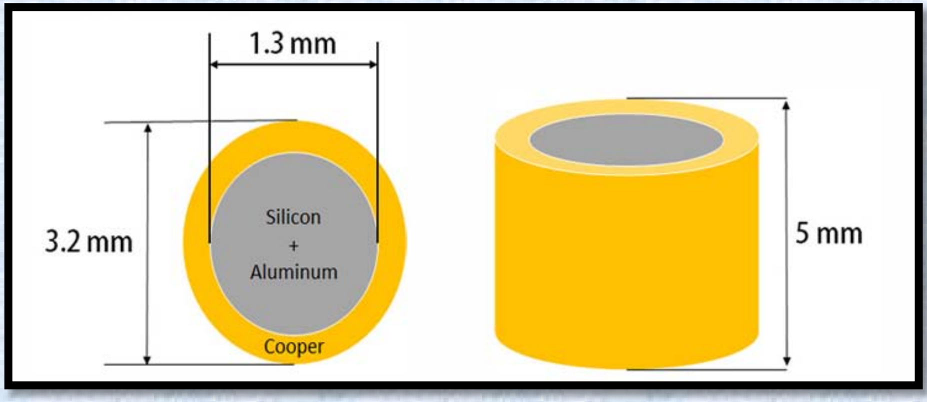
- BeO. SIRCA port: neutron flux of 2.26 x 10^{11} n/cm^{2}s (30 min/sample and 120 min/sample).
- Uracil. SINCA port: neutron flux of 4.42 x 10^{12} n/cm^{2}s (20 s/sample) .
- Graphite. B1 port. neutron flux of 2.3 × 10^{13} n/cm^{2}s (10 h/sample and 2 h/sample (Cd container)).

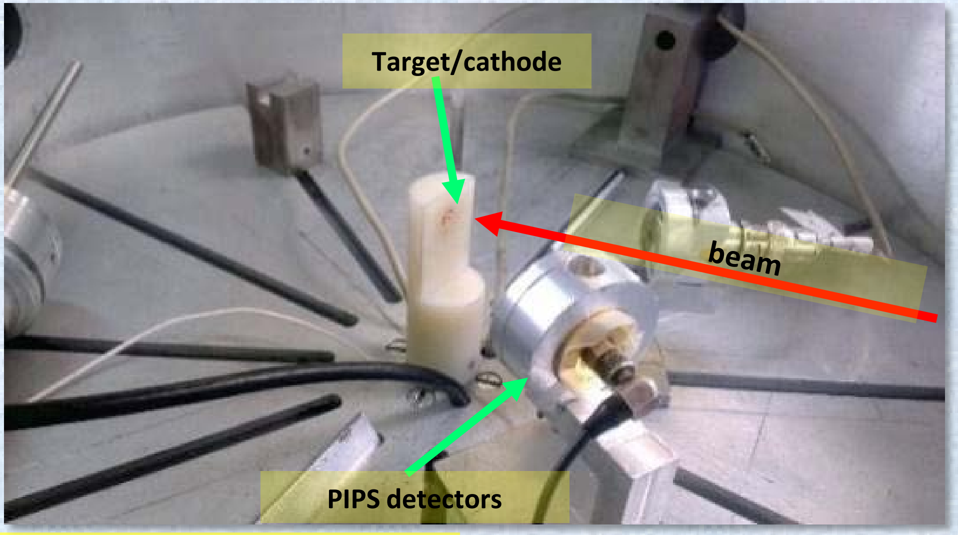
$^{28}Si(d,\alpha)^{26}Al$ reaction.

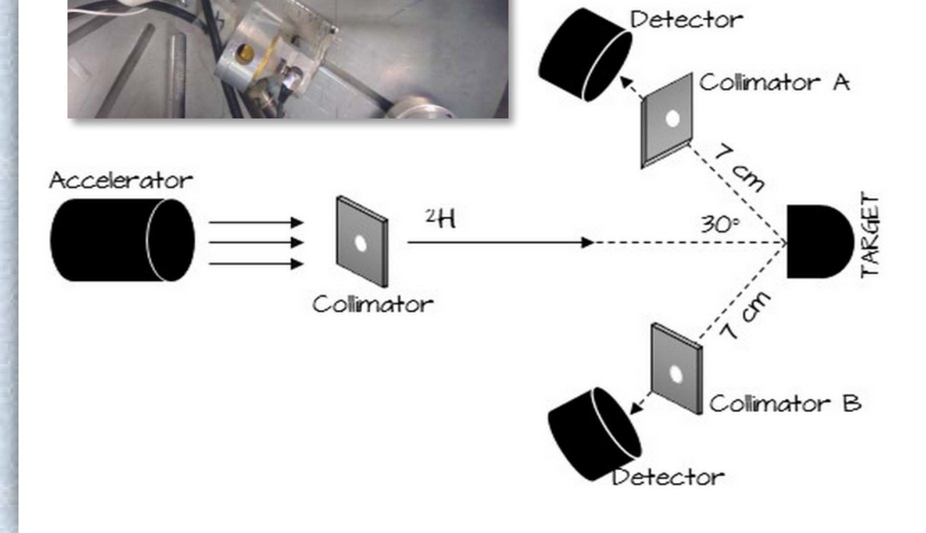
- Two measurements using two different facilities:
  - Van der Graaff 5.5 MV, (Lab. CGF @ IFUNAM, Mexico City)
  - CN-Tandem 6 MV, (ININ, Ocoyoacac Edo. Mex.).
  - Both facilities can produce deuterium beams of 1 and 2 MeV (~ 1 μA)
  - For $^{25}Mg(p,\gamma)^{26}Al$ the new low-energy beam line of LEMA will be used.

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

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

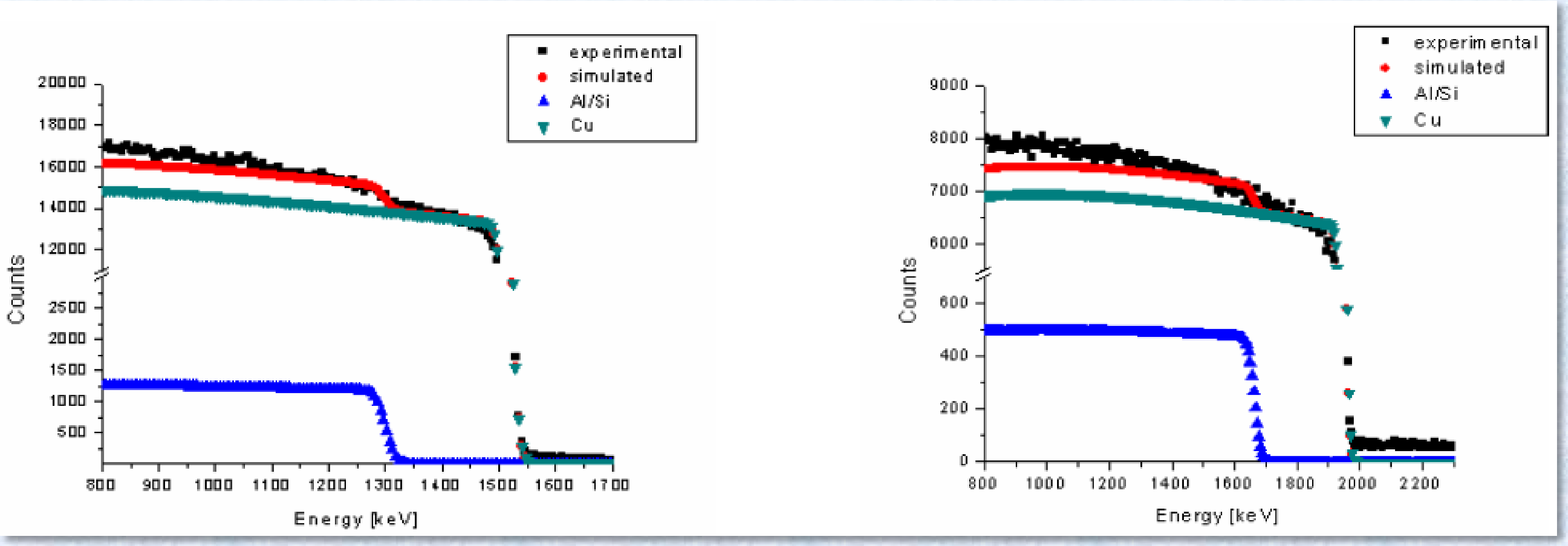






First attempt to measure $^{28}Si(d,\alpha)^{26}Al$ reaction

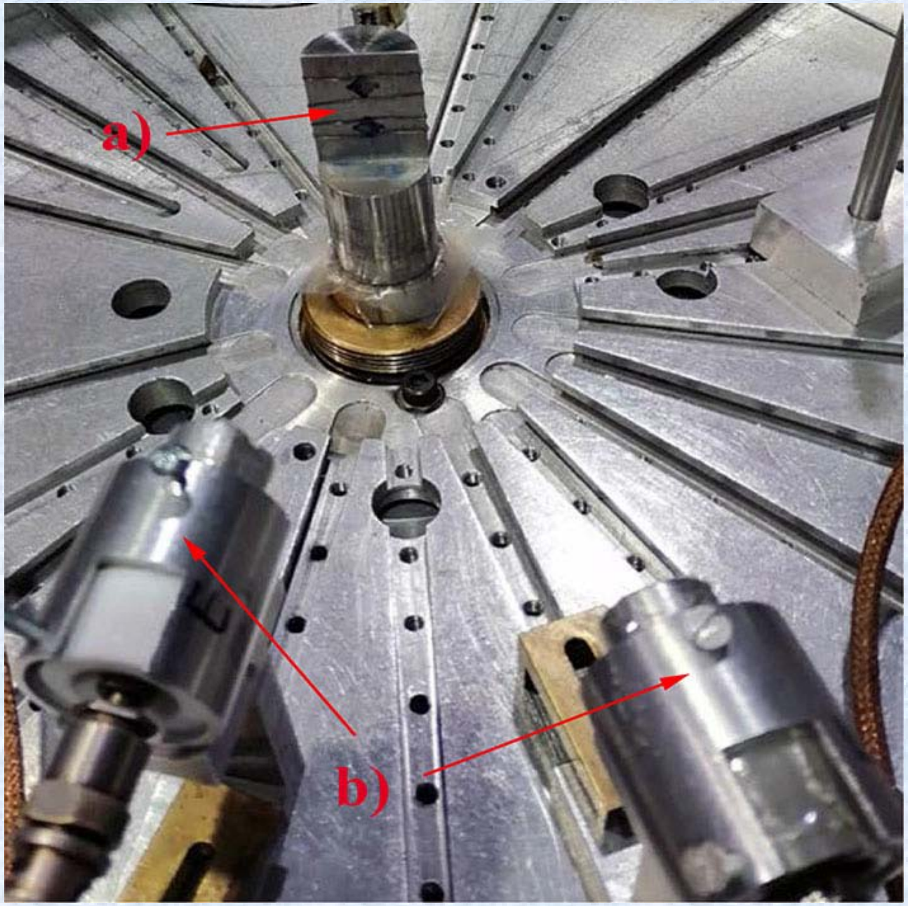
- However, due to the small size of the sample, most of the beam (till 80%) was impinging the cooper container (cathode).
- The consequences were ^{26}Al cross section of 3.9(4) μb (1.1 MeV), 1.5(2) μb (1.5 MeV) and 1.3(1) μb (1.8 MeV).



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)

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

- 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 Al_2O_3).



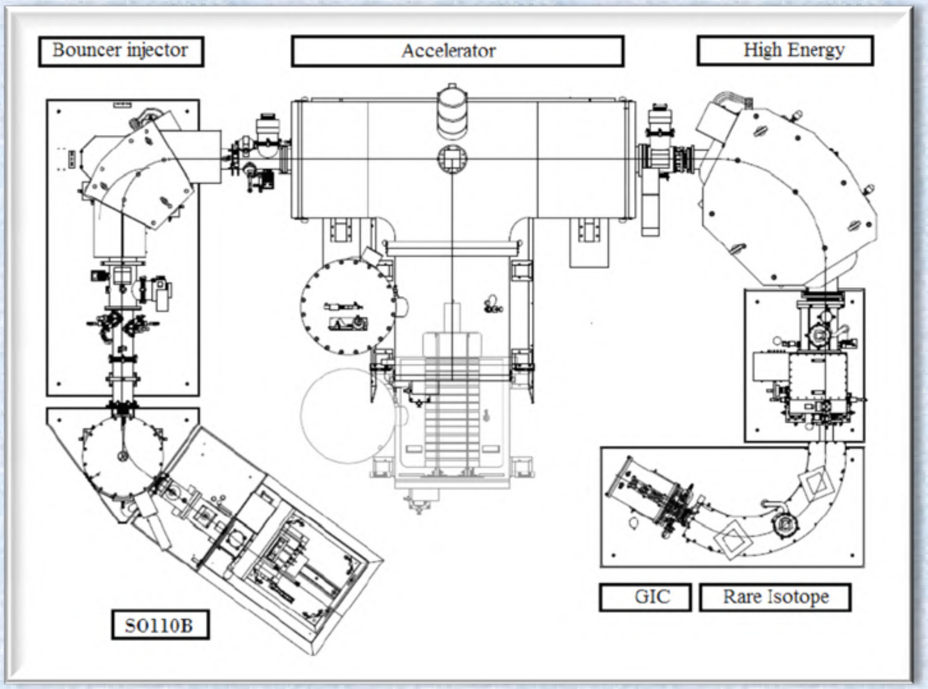
a) New target older and Si waffles.

b) Silicon detectors (500 µm thickness)

2nd part: AMS measurement

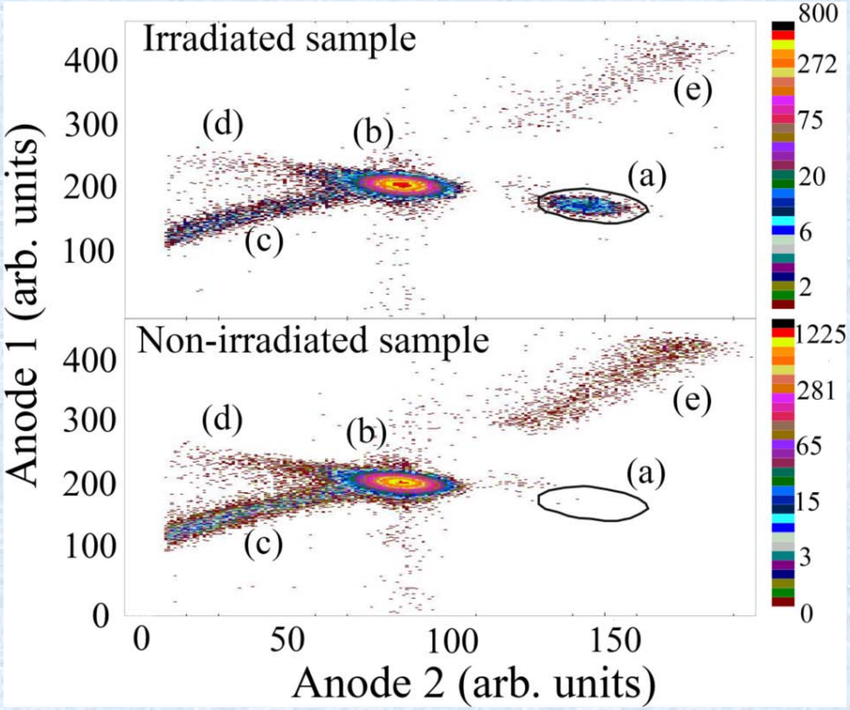
The LEMA facility.

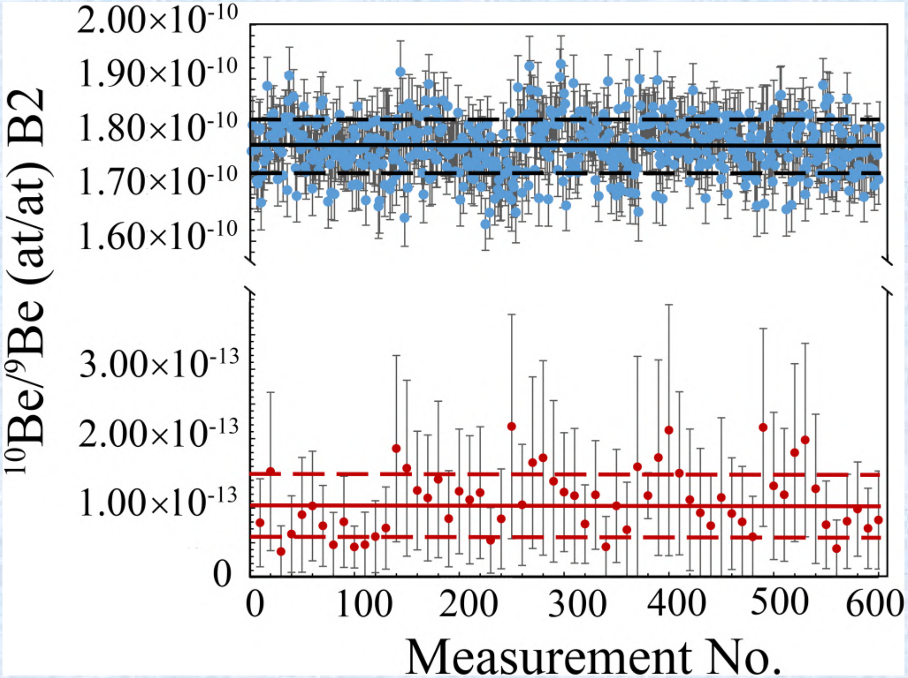
- The National Laboratory of Accelerator Mass Spectrometry (LEMA) was commissioned on 2013.
- It was placed at the Physics Institute UNAM along with other previous accelerators.
- A tandetron of 1 MV (HVEE) equipped with peripheral laboratories:
    - for the cleaning and chemical samples preparation;
    - 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}Be, ^{14}C, ^{26}Al, ^{129}I and Pu isotopes.



Results for neutron capture reactions.

BeO samples.





ΔE-E spectra from gas detector of LEMA system.

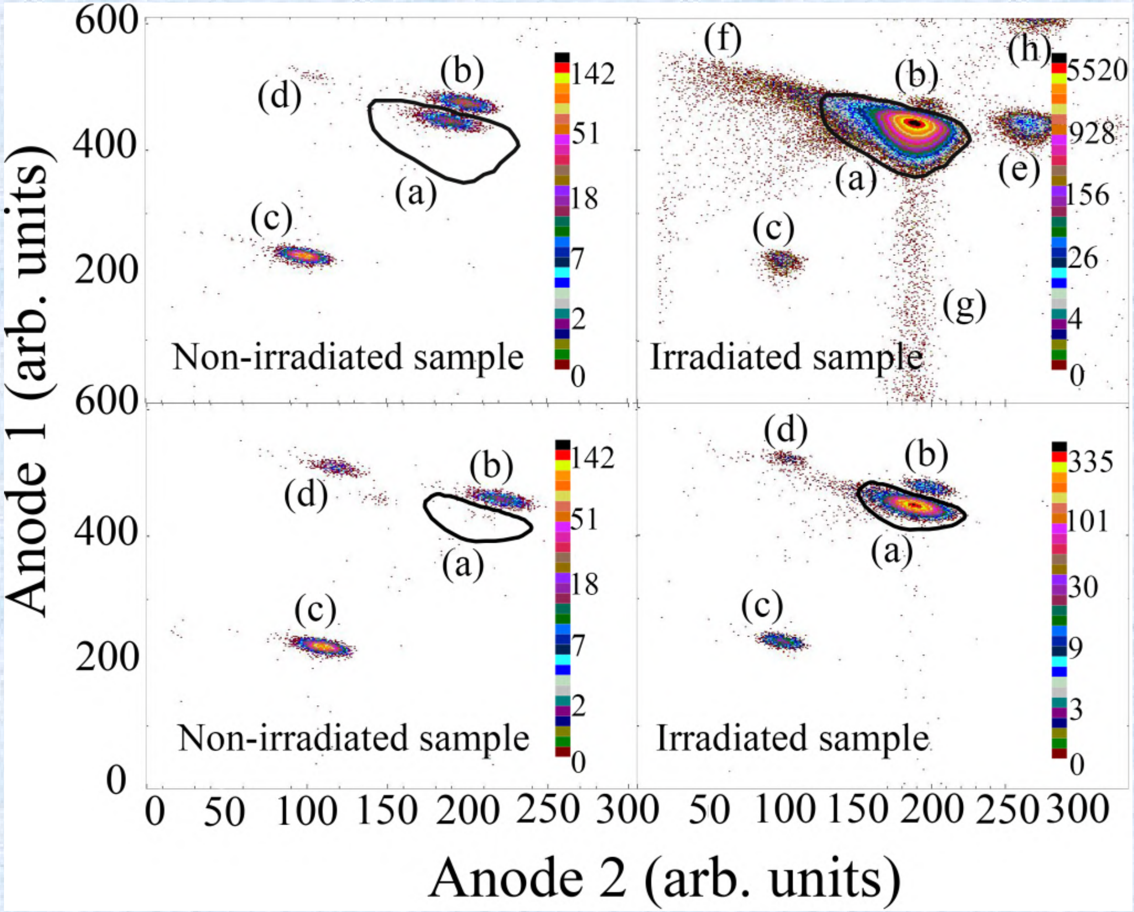
Events enclosed in black polygon are ^{10}Be counts.

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

ΔE-E spectra from gas detector of LEMA system.

Events enclosed in black polygon are ^{14}C counts.

Reaction cross sections

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

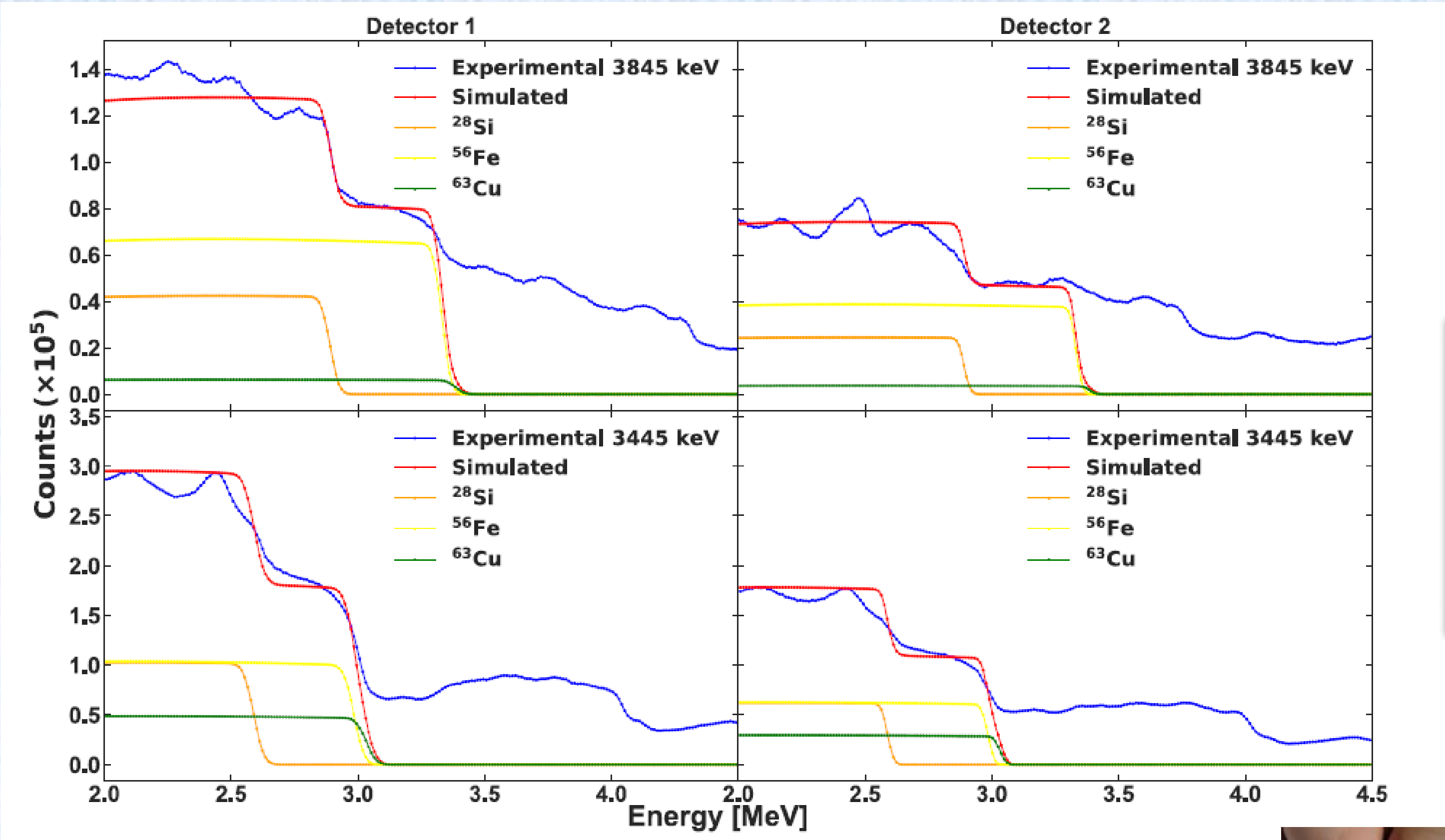
- Cross section found for $^{14}N(n,p)^{14}C$ reaction is in agreement with the previous measured values.
- Cross section found for $^{13}C(n,\gamma)^{14}C$ it is far from the values reported in the literature. The discrepancy could be related to the production of ^{14}C by neutron reactions in Nitrogen,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

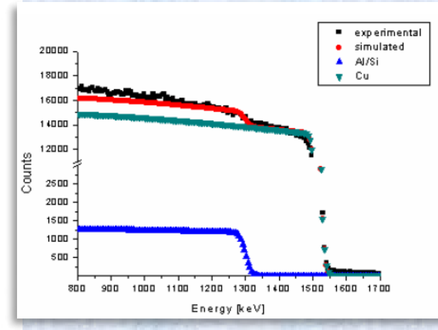
PHYSICAL REVIEW C **102**, 044601 (2020)

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

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

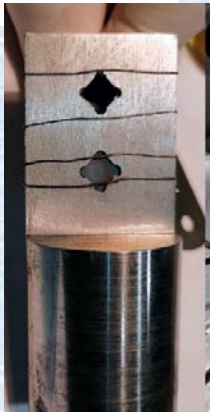
$^{28}Si(d,\alpha)^{26}Al$ results.



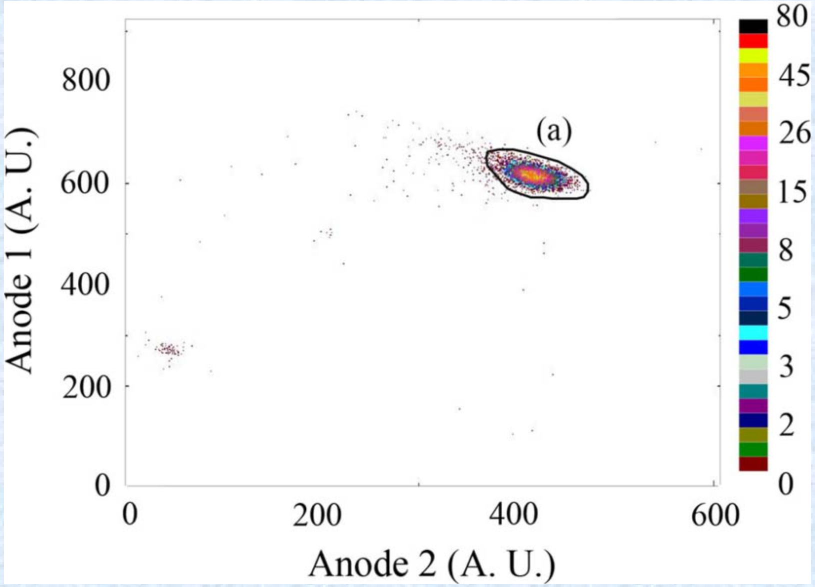


RBS analysis of deuterons scattered at 165º by Si target and other elements.

For this 2nd attempt, the beam on Si target for all the measured energies was ~ 70% (most of the beam was on Si).

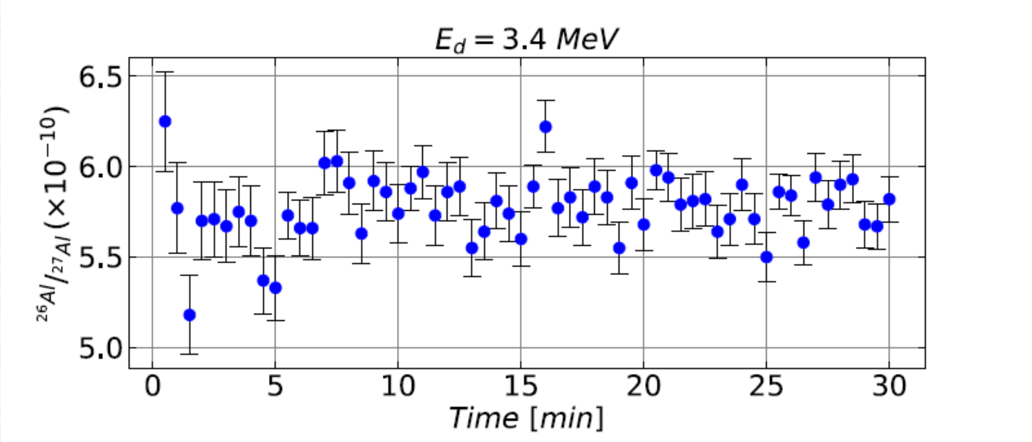


$^{28}Si(d,\alpha)^{26}Al$ results.
Al_2O_3 samples



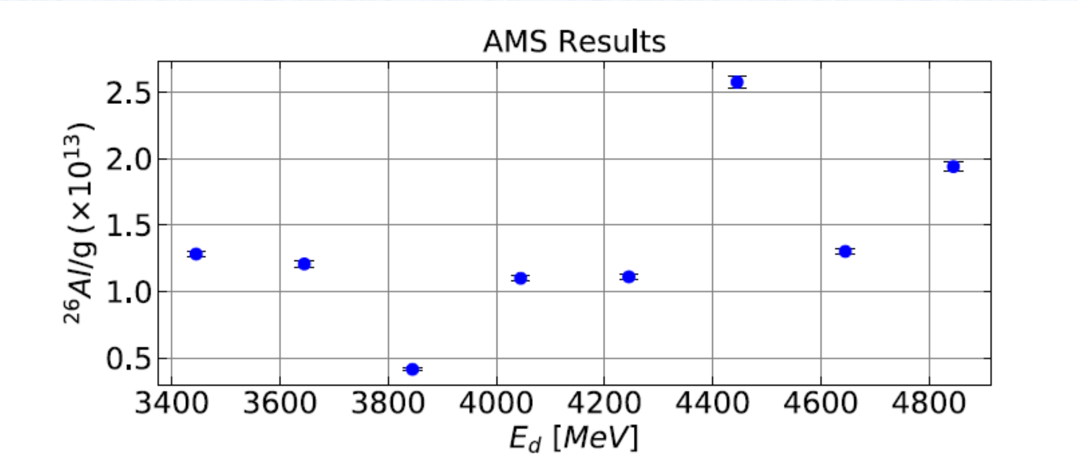
ΔE-E spectra from gas detector of LEMA system.

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



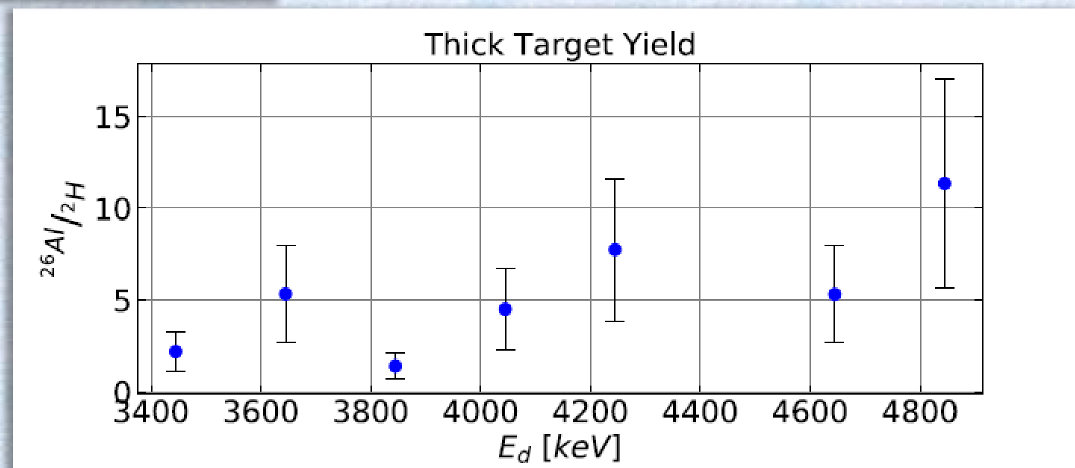
Data from irradiated samples.

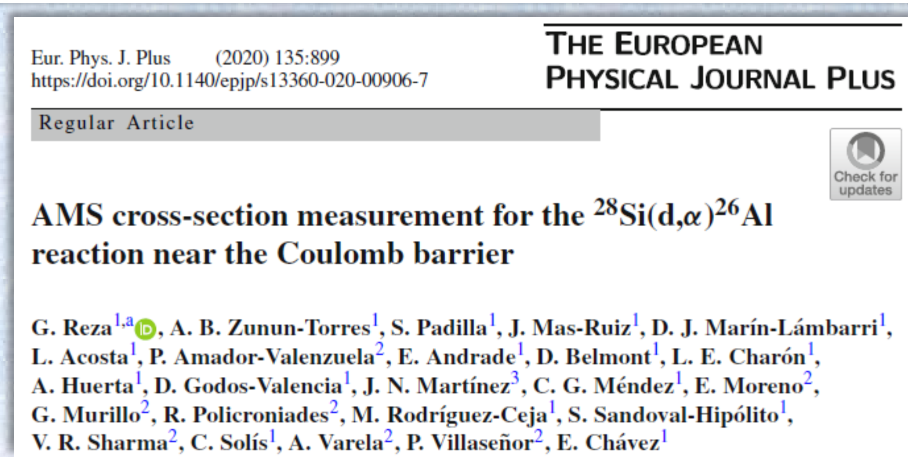
Measure of the ^{26}Al concentrations



- ^{26}Al concentrations can be well measured with AMS. The uncertainties grows noticeably when ^{26}Al events are normalized with the thick target.

- Larger uncertainties may come from the poor determination of the deuteron flux.





Eur. Phys. J. Plus (2020) 135:899
https://doi.org/10.1140/epjp/s13360-020-00906-7

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

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

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

Improvements and further ^{26}Al measurements.

- To achieve the total cross section for (d,α) 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 (ΔE-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,γ) reaction at 400 keV (in the new LEMA beam-line is the next to measure. Natural Mg targets are under chemical test.

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}C and ^{10}B production respectively) were well measured, showing the effectiveness of the method.
- Particularly for **$^{9}Be(n,\gamma)^{10}Be$ reaction**, we achieve the first direct measurement of the total cross section, which is in agreement with previous indirect measurements.
- **$(d,\alpha)^{26}Al$ 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 $(p,\gamma)^{26}Al$ at 400 keV, which is crucial for the understanding of the ^{26}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.

Instituto de Física, Universidad Nacional Autónoma de México, Mexico.

Instituto Nacional de Investigaciones Nucleares, Mexico.

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