Reaction production + AMS: An alternative method to study low energy reactions. ^{26}Al as a test case

L. Acosta[1,2,*], *V.* Araujo-Escalona[3], *E.* Chávez[1], *E.* Andrade[1], *L.* Barrón-Palos[1], *F.* Favela[1,2], *M.A.* Flores[1], *J.* García-Ramírez[1], *A.* Huerta[1], *O.* de Lucio[1], C. Méndez-García[1], *M.E.* Ortiz[1], S. Padilla[1], *A.M.* Sánchez-Benítez[4], *P.* Santa Rita[1], and *C.* Solís[1]

[1]Instituto de Física, Universidad Nacional Autónoma de México, A.P. 20-364, Cd.Mx. 01000, Mexico
[2]Istituto Nazionale di Fisica Nucleare, Sezione di Catania, I-95123 Catania, Italy
[3]KU Leuven, Instituut voor Kern-en Stralingsfysica, 3001 Leuven, Belgium
[4]Facultad de Ciencias Experimentales, Universidad de Huelva, E-21071, Huelva, Spain

Abstract. Considering the importance of the ^{26}Al nuclei in Astrophysics, in this work, preliminary results regarding a campaign of measurements related with this radioisotope production, are presented. We have taken advantage of two different facilities: first, the radio-nucleus is produced by means of irradiation of targets selected in correlation with particular reactions; once the enrichment with ^{26}Al was made, the targets are analyzed in an AMS machine to obtain the concentration of ^{26}Al produced during the irradiation. With this off-line method, it is possible to measure acceptable small cross sections of a selected low energy reaction. In this work, our preliminary results for three different energies of ^{28}Si(d,α)^{26}Al reaction cross sections are shown, as well as our first considerations to commence with measurements of ^{25}Mg(p,γ)^{26}Al reaction cross sections below 1 MeV.

1 Introduction

The ^{26}Al is a long-lived radioisotope ($T_{1/2}$ = 0.716 My). The characteristic gamma at E_γ = 1.809 MeV, following its β+ decay to ^{26}Mg, has been observed for decades in the galactic plane, giving evidence of presently undergoing nucleosynthesis. The detection of the radiation generated by this decay allows to trace the ^{26}Al production sources in the Milky Way, and impose with this, constrains to the existing nucleosynthesis models [1]. This radioisotope is present for instance, in the stars where there is H, C and Ne fusion at high temperatures; besides, indications of extinct ^{26}Al have been found in meteorites where it could be deposited or created *in situ* [2].

Though many studies regarding ^{26}Al have been carried out, some discrepancies still remain about its production in explosions of massive stars. There are important gaps in knowledge regarding the kind of events or environments which most contribute to its production (Wolf-Rayet, novae, asymptotic giant branch, supernovae explosion, etc.) [3].

---

[*] Corresponding author: acosta@fisica.unam.mx

Many important reactions to produce ^{26}Al happen at very low energies, making difficult to get an approach of the cross section by using standard spectroscopic methods to measure them. Several γ resonances, in case of ^{25}Mg(p,γ)^{26}Al appear for instance, below 500 keV, a region where real γ-ray signal may be coupled with background of a conventional detection system.

In order to overcome the technical difficulties afore mentioned, an alternative technique proposed by Arazi et al. [1] has been identified. This technique is particularly useful for measuring extremely low cross sections of reactions that produce long-lived radionuclides, like ^{26}Al. In [1], authors used ^{25}Mg(p,γ)^{26}Al reaction to produce the radio-nucleus by means of a low energy proton beam interacting with a MgO target. The irradiated target is subsequently analyzed for its ^{26}Al content by using accelerator mass spectrometry technique (AMS). This technique allow us to yield information about the number of ^{26}Al nuclei which were produced previously, during the irradiation. To achieve this goal, the [1] authors used a chemical separation of the Al from the MgO target including ^{27}Al as carrier, in order to normalize a ratio of events (^{26}Al/^{27}Al) by using AMS. The final composed to be employed as material for the negative-ion sputter source of the AMS system was Al_2O_3. The ^{26}Al/^{27}Al ratio obtained with AMS can be later traduced as a cross section of the reaction to be studied.

In the following section the main characteristics of our measurements are described, which were based on the technique mentioned above, in order to obtain cross section values for the (d,α) reaction related as well with the ^{26}Al production. In section 3 our preliminary results are shown and after that, at the end of such section, our perspectives to develop other measurements regarding (p,γ) reaction (always measuring ^{26}Al nuclei with AMS), are also described. We dedicated the section 4 to present the main conclusions extracted from the exposed measurements.

Fig. 1. CN-Van de Graaff Accelerator 5.5 MV, Carlos Graef Laboratory (left picture) and Accelerator Mass Spectrometry National Laboratory, LEMA (right picture) at Physics Institute, UNAM, Mexico City. The Van de Graaff was used for the irradiation of the samples, later analysed in the AMS facility (see text for details).

2 Experimental procedure

In the CN-Van de Graaff Carlos Graef Laboratory of IF-UNAM at Mexico City (left picture, Fig. 1), 300 nA beams of protons, deuterons, ^{3}He and ^{4}He can be currently produced between 0.8-3.0 MeV energy range. Considering this, the performances of this facility are particularly appropriate to study the production of ^{26}Al by means of ^{28}Si(d,α)^{26}Al reaction at low energies (Q = 1.43 MeV). The study of (d,α) reaction at low energies 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 [2]. Even if the cosmic rays flux of deuterons compared with cosmic rays flux of protons is really low (2 to 5 % [4, 5]), we consider interesting to know with precision the cross sections related with the (d,α) reaction. Moreover, the high purity Silicon powder (used as target for this reaction) shows a very stable behaviour when interacts with stable beams (the case of the irradiation in the first step) and allows the production of a stable Al current in the sputter negative ion cesium source (which is the case of AMS ion source to be used for the second part of the measurement).

2.1 Target preparation and irradiation

As a first step, we decided to carry out the irradiation directly on the container capsule of the sample to be irradiated, which later is directly used as "cathode" in the AMS system. In this context, we did not perform the chemical process referred in [1] to separate the produced ^{26}Al. Instead of that, we filled the cathode with an homogeneous mixture of powder made of a combination of high purity silicon and aluminium powders. The latter was included to normalize the ^{26}Al produced during the irradiation. A series of target/cathodes were mounted (one by one) inside a vacuum chamber to be irradiated for periods of 2 hours with a deuterium beam of an average intensity of 200 nA. A detailed description of this procedure is well described in [6, 7]. In order to monitor the reaction behaviour, two PIP-silicon detectors were placed symmetrically at 150º in both backward sides of the target/cathode. The sketch and a picture of this experimental setup are shown in Fig. 2. A typical RBS spectrum, where scattering on Al/Si can be well identified, is shown in Fig. 3. Here it is worth mentioning that a considerable fraction of the beam intensity is scattered on the copper, according to the spectrum in Fig. 3. Nevertheless, with the spectrum it is possible to estimate the correct amount of beam that could be exploited using a fit program (SIMNRA [8] in this work) along with a numerical calculation. A detailed description of such analysis can be consulted in reference [7].
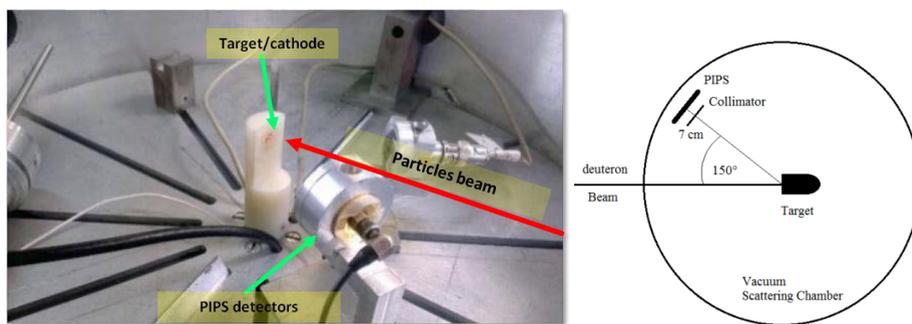

Fig. 2. Experimental setup for the first step of the technique, where a deuterium beam irradiates the target to produce ^{26}Al. Picture (left panel) and sketch (right panel). (see the text for details).

2.2 Counting of ^{26}Al at the AMS system

The Accelerator Mass Spectrometry National Laboratory (LEMA) at IF-UNAM, Mexico City, is a 1 MV tandetron machine, manufactured by HVEE (see right picture at Fig. 1). It is well calibrated to achieve very small concentrations of ^{14}C, ^{10}Be, ^{26}Al, ^{129}I and Pu isotopes [9]. With LEMA is possible to discriminate an ^{26}Al event among 10^{14} ^{27}Al ones.

This characteristic makes LEMA to be an adequate system to test the technique proposed here.
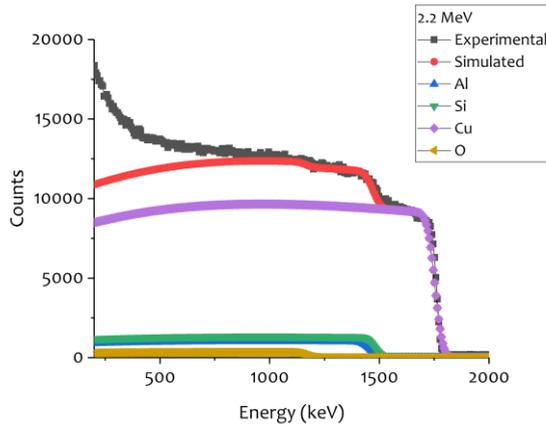
Fig. 3. Typical RBS spectrum (black squares) fitted with SIMNRA (red circles) for a deuterium beam at E_{lab} = 2.2 MeV. Straight and inverted triangles (green and blue lines) account for the contribution of the scattered deuterium in the Al/Si target while diamonds (purple line) account for the scattering on the container capsule, made of copper.

Once the cathodes are irradiated they can be placed in the carrousel for cathodes of LEMA to begin the interaction with a negative Cs ion source in order to produce Al beam. This cathodes are complemented with enriched ^{26}Al cathodes and blanks (both used as standard to calibrate the isotope separator). The number of events related with ^{26}Al are counted by using the ΔE-E discrimination technique, by means of a gas detector placed at the end of the line in the AMS system. The value expected for the ^{26}Al/^{27}Al ratio in the case of the standard was 6.72×10^{-11}, which was well reproduced for the present measurements. In Fig. 4 a typical ΔE-E uncalibrated spectrum is depicted, where the detected events related exclusively with ^{26}Al nuclei for the sample used as standard, can be clearly seen inside the black region of interest.
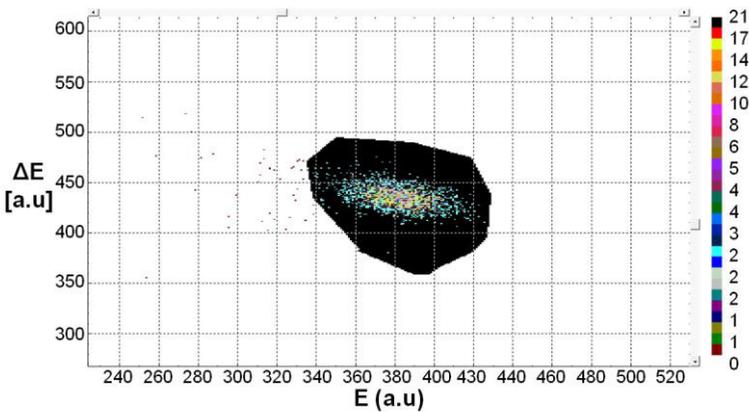
Fig. 4. Typical ΔE-E spectrum for a standard sample used to fine tune the AMS system. The coloured events enclosed by black region are identified as ^{26}Al counts.

4

3 Preliminary results

Once all possible variables involved in the measurement processes have been taken into account, it is feasible to obtain preliminary values for cross sections related with some specific irradiation energy for ^{26}Al production. The results reported here were obtained for three different energies: 1.1 MeV, 1.5 MeV and 1.8 MeV. The estimated values are 3.9(4) µb, 1.5(2) µb and 1.3(1) µb, respectively. The largest value appears for the lowest energy, showing probably a value closer to a maximum.

The preliminary cross sections estimated could be considered too small for the studied reaction, however to the best of our knowledge they do not exist published values to establish any kind of comparison. It is important to mention that irradiation on the target is in all cases concentrated in the surface of the cathodes, penetrating some tens of Amstrong inside the target material. In this situation, part of the produced radioisotope could get lost at the first interaction with the ion source at the AMS system. Therefore, to validate this methodology, it would be necessary to reach reproducible results repeating the same process, with increasing irradiation period to ensure the radioisotope production, even at the surface level. In order to compare both processes, we will try as well the chemical separation of the radioisotope produced (as it was done in [1] for Mg target), and fill a cathode with the obtained solution. Both goals are nowadays in progress. For the moment we can affirm that we have the capability to address this two-steps method to obtain a value for a determined reaction cross section, particularly for reactions that require of low background systems to be directly measured.

3.1 Perspectives for new measurements involving ^{26}Al reactions

As part of a parallel study, some measurements related with the (p,γ) reaction, previously mentioned, are in progress. Testing this reaction will allow to reproduce some of the values reported in [1,10] by using lower energy AMS system. ^{25}Mg(p,γ)^{26}Al reaction is the prevailing reaction in the Mg-Al chain, i.e., this is a very important reaction for the nucleosyntesis processes. At temperatures between 0.1 and 1.5 GK in the stellar processes, the ^{26}Al production rate depends on very weak resonances, doing its determination a very difficult task when are used on-line detection techniques to prompt the γ -ray emission.

In spite of those difficulties, quite efforts inside big collaborations have performed to achieve good measurements of several strengths of resonances related with ^{25}Mg(p,γ) ^{26}Al, combining the on-line and off-line methods [11, 12].

During the last 20 years, most of the interest resonances have been well measured. However, there still remains some discrepancies for specific values as, for instance, 197 keV, 417 keV and 435 keV resonance energies. Considering our present systems, we are able to obtain the strength of resonances around 400 keV, by using a similar methodology that was used in [1, 11].

Since October 2017, a new beam line was mounted and commissioned as part of the Separator Spectrometer in the LEMA laboratory. Before this date, the Spectrometer was entirely dedicated to AMS studies. With this new line, it is possible to produce intense low energy beams of protons: 300 to 2200 keV with 1 µA of stable current. With this conditions it seems feasible to develop the irradiation and later the AMS analysis by using the same accelerator. Considering the very recent implementation of this new beam line, the setting up of such measurements is presently at the very beginning.

4 Conclusions

In this work an alternative method to achieve relevant information regarding particular reactions of difficult access with conventional measured techniques was raised. The proposed methodology combines the use of accelerated low energy beams with accelerator mass spectrometry. The main goal of the used technique is to obtain with the combination mentioned, absolute cross sections of low energy reactions where a selected radioisotope is involved.

To test the proposed technique, the ^{28}Si(d,α)^{26}Al reaction was selected. Considering that such reaction involves ^{26}Al nuclei, which plays an important role in astrophysical processes, the scientific interest is justified. Our preliminary results have shown very small values for the cross sections of the three different measured energies (1.1 MeV, 1.5 MeV and 1.8 MeV). However, we could not find experimental values to corroborate the present results. Works are under progress in order to validate the technique at IF-UNAM facilities. In parallel, we are working in the preparation to start some other measurements regarding the (p,γ) reaction, related as well with the study of ^{26}Al production.

Acknowledgments

References

1. A. Arazi et. al., Phys. Rev. C. **74**, 025802 (2006).

2. T. Lee, D. a. Papanastassiou, and G. J. Wasserburg, Geophys. Res. Lett. **3**, 1 (1976).

3. J. Knödlseder et. al., Astron. and Astrophys., **344** (1999).

4. B.J. Teegarden J. of Geoph. Res. **72**, 19 (1967).

5. J.Z. Wang et al., Astrophs. J. **564**, 244 (2002).

6. V. Araujo-Escalona et. al., J. of Phys.: Conf. Ser. **730** (2016).

7. V. Araujo-Escalona et. al., Phys. Proc. **90** (2017).

8. M. Mayer, Amer. Inst. of Phys. Conf. Proc. **475** (1999).

9. C. Solís, E. Chávez, M.E. Ortiz, A. Huerta, E. Andrade, E. Barrios. Nucl. Inst. Meth. Phys. B, **331** (2014).

10. D. C. Powell, et al., Nucl. Phys. A **644**, 263 (1998).

11. B. Limata et. al., Phys. Rev. C **82**, 015801 (2010).

12. F. Strieder et. al., Phys. Lett. B **707** (2012).