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# Towards the measurement of the $^{13}\text{C}(\text{d}, \text{p})^{14}\text{C}$ cross section using AMS

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**Abstract.** A plan to study the total cross section for the  $^{13}\text{C}(\text{d}, \text{p})^{14}\text{C}$  nuclear reaction has been developed for energies in the center-of-mass frame between 133 and 400 keV. The proposed experiment will use a deuterium beam (1 - 3 MeV of energy) from the Instituto de Física-UNAM 5.5 MV Van de Graaff accelerator and the produced  $^{14}\text{C}$  will be afterwards measured by AMS technique in the LEMA-UNAM (HVEE 1 MV Tandetron). One of the main goals is to study the performance of the LEMA-UNAM facility in the cross section measurement in comparison with other data reported in the literature, measured by other techniques. In this work we present the current status of these studies. The relevance of the  $^{13}\text{C}(\text{d}, \text{p})^{14}\text{C}$  reaction in the study of compound nucleus formation as well as in some astrophysics scenarios, and the importance of the development of the AMS technique to measure cross sections of nuclear reactions of astrophysical interest in Mexico are also discussed.

## 1. Introduction

Knowing the cross section of nuclear reactions is important in nuclear physics because it helps to have a better understanding of nuclear structure. In nuclear astrophysics, it provides information about the processes that take place in the cosmos. Unfortunately, the cross section of many nuclear reactions at the energies of interest remain poorly known due to the challenges implicated in the measurement of very low cross sections or in the measurement of cross sections of nuclear reactions that involve radioactive nuclei. Therefore, the development of efficient techniques to measure reaction cross sections is necessary. The use of the AMS technique to determine the presence of an isotope of interest, produced by a nuclear reaction in a previous irradiation of the sample is gaining more scientific interest as a tool to study nuclear reactions with small cross sections that are difficult to measure using other techniques, besides it offers a complementary tool for studying long-lived radionuclides [1]. Several studies have been published on the use of the AMS technique to study nuclear reactions [1] [2] [3] [4].

This paper presents the preparation that is currently taking place towards the first measurement of the cross section of the  $^{13}\text{C}(\text{d}, \text{p})^{14}\text{C}$  nuclear reaction at low energies (133 - 400 keV in the center-of-mass system) using the AMS technique.

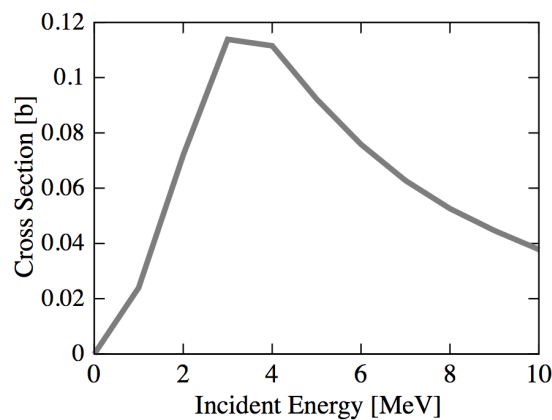
What we know about the cross section of the  $^{13}\text{C}(\text{d}, \text{p})^{14}\text{C}$  nuclear reaction is largely based on very limited experimental data. Hence, one of our goals is to widen experimental knowledge of this reaction. Previous work on the  $^{13}\text{C}(\text{d}, \text{p})^{14}\text{C}$  reaction has focused on the angular momentum distribution and yield [5][6], and the excitation function measurement [7].



This reaction involves deuterium, which is an important ingredient in the primordial nucleosynthesis that took place within the first 3 minutes after the Big Bang [8]. Although the  $^{13}\text{C}(d, p)^{14}\text{C}$  reaction is not considered among the main reactions that take place in the standard CNO nucleosynthesis, extended models where subleading reaction channels are considered seem to find larger concentrations of  $^{13}\text{C}$  and  $^{14}\text{C}$  due to a more efficient carbon burning process that involves (d, p) reactions on  $^{12}\text{C}$  and  $^{13}\text{C}$  [9].

Furthermore, this nuclear reaction is of interest since it allows to study the formation of compound nucleus. The first studies on compound nucleus formation in the  $^{13}\text{C}(d, p)^{14}\text{C}$  nuclear reaction from 1 to 3 MeV in the laboratory frame of reference was carried out in 1956 by Marion and Weber [6].

Figure 1 shows the cross section for the  $^{13}\text{C}(d, p)^{14}\text{C}$  nuclear reaction, which is of the order of ten mb between 1 and 3 MeV.



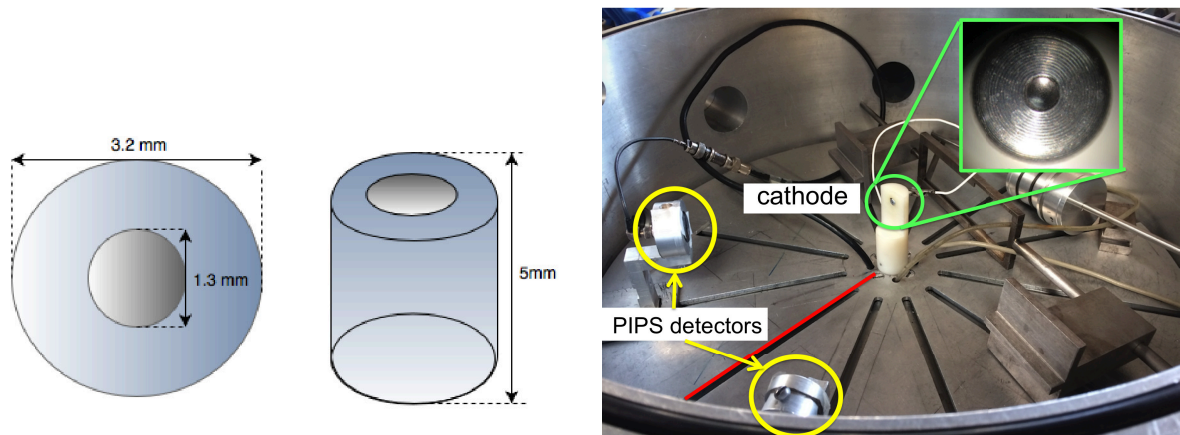
**Figure 1.** Total cross section for the  $^{13}\text{C}(d, p)^{14}\text{C}$  nuclear reaction at energies between 0 and 10 MeV in the laboratory frame of reference. Data retrieved from ENDF (TENDL - 2014) [10].

## 2. Experiment

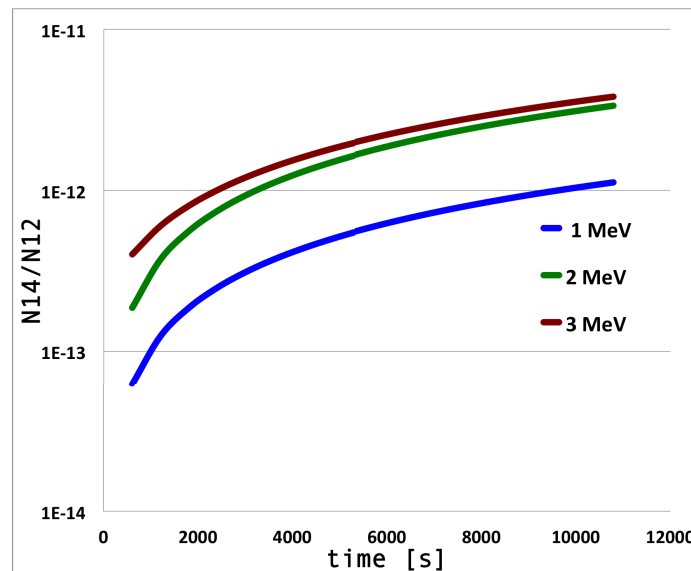
Our purpose is to irradiate graphite (98.9%  $^{12}\text{C}$ , 1.1%  $^{13}\text{C}$ ) samples with a deuterium beam with energies between 1 and 3 MeV. In order to avoid processing the graphite after irradiation for AMS analysis, the aluminium cylindrical cathodes containing graphite, used in the negative-ion source of the AMS accelerator, are directly irradiated at the Van de Graaff accelerator. Approximately 4.5 mg of graphite are used per cathode. The surface corresponding to graphite is  $\sim 1.33\text{mm}^2$ . The cathode geometry is shown in Figure 2. Using two CANBERRA's Passivated Implanted Planar Silicon detectors (PIPS), Rutherford Backscattering Spectrometry (RBS) will be performed to determine how much of the sample's surface has actually been irradiated.

Despite the low content of  $^{13}\text{C}$  in graphite, and the relatively low deuterium-beam currents that can be obtained at the IFUNAM 5.5 MV Van de Graaff ( $\sim 3.12 \cdot 10^{10}$  particles/s $\cdot\text{cm}^2$ ), it is possible to achieve relative concentrations of  $^{14}\text{C}$  ( $^{14}\text{C}/^{12}\text{C}$ ) that are of the order of  $10^{-12}$  in relatively short times (a few hours). These concentrations are within the sensitivity range of LEMA, where relative concentrations as low as  $10^{-15}$  for  $^{14}\text{C}/^{12}\text{C}$  can be measured.

A plot of the calculated time variation of the relative concentration of  $^{14}\text{C}/^{12}\text{C}$  is shown in Figure 3. As it can be seen, relative concentrations of  $10^{-12}$  can be achieved after a few hours of irradiation with a 500 nA beam impinging the  $1.33\text{mm}^2$  cross sectional area of graphite on the aluminum cathode surface.



**Figure 2.** Diagram of a graphite-filled aluminium cathode (left); Set-up configuration for RBS(right)



**Figure 3.** Plot of  $N_{14}/N_{12}$  vs. time for 1 MeV (blue), 2 MeV (green) and 3 MeV (red) for 10 hours of irradiation.

The variation with time of the  $^{12}\text{C}$ ,  $^{13}\text{C}$  and  $^{14}\text{C}$  concentrations is described by the equations below:

$$\frac{dN_{12}}{dt} = -N_{12} \Sigma_{12} \phi \quad , \quad (1)$$

$$\frac{dN_{13}}{dt} = N_{12} \sigma_{13} \phi - N_{13} \Sigma_{13} \phi \quad , \quad (2)$$

$$\frac{dN_{14}}{dt} = N_{13} \sigma_{14} \phi - N_{14} \Sigma_{14} \phi \quad . \quad (3)$$

where  $N_{(12,13,14)}$  correspond to the concentrations of  $^{12}\text{C}$ ,  $^{13}\text{C}$ , and  $^{14}\text{C}$  at a given time  $t$ ,  $\Sigma_{12,13,14}$  are the sums of the cross sections of the reactions that consume  $^{12,13,14}\text{C}$  ((d,p),(d,n),(d, $\gamma$ ) and (d, $\alpha$ )),  $\sigma_{13,14}$  are the cross sections of the nuclear reactions that produce  $^{13}\text{C}$  and  $^{14}\text{C}$ , and

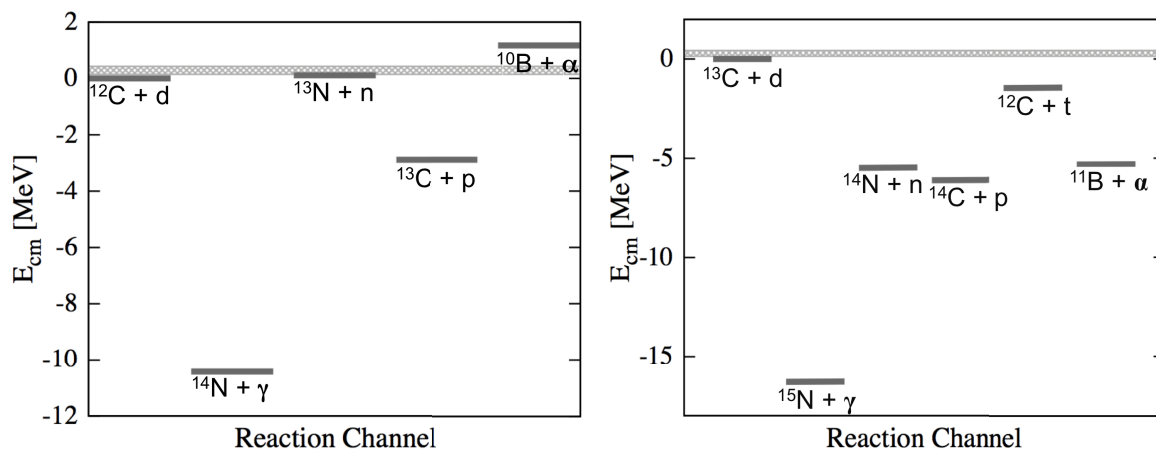
$\phi \approx 6.4 \times 10^{13}$  particles/s  $\cdot$  cm<sup>2</sup> is the flux of deuterons impinging on the graphite surface of the cathode (corresponding typically to a 500 nA deuterium beam after collimation).

In Figure 4, the excitation energy is shown for the possible reaction channels, which can be determined initially by the laws of conservation of energy and changing from the laboratory system to the center-of-mass reference frame to obtain:

$$K_{thr(c.m.)} = -Q \left( 1 + \frac{m_p}{m_t} \right) \quad (4)$$

where  $K_{thr(c.m.)}$  is the threshold energy of the projectile,  $Q$  the  $Q$  – value of the reaction channel,  $m_p$  the mass of the projectile and  $m_t$  the mass of the target.

Since natural graphite is a mixture of <sup>12</sup>C and <sup>13</sup>C, both <sup>12</sup>C(d, p) and <sup>13</sup>C(d, p) nuclear reactions take place. Therefore, we consider the reaction channels of each.



**Figure 4.** Excitation energy for the reaction channels of <sup>12</sup>C(d, p) and <sup>13</sup>C(d, p) in the center-of-mass reference frame. The gray band illustrates the energy region in which our study will take place.

### 3. Conclusions

A campaign of irradiation of cathodes containing graphite with a deuterium beam is planned to be performed at the 5.5 MV Van de Graaff accelerator in April, 2017, when we expect to be able to study the cross section for the <sup>13</sup>C(d, p) reaction at different beam energies between 1 and 3 MeV in the laboratory frame. The development of the AMS technique to measure cross sections of nuclear reactions is important since there is a large number of cross sections of astrophysical interest that could be studied with this method. Additionally, developing this technique would allow us to take advantage of the infrastructure that we have in Mexico to conduct studies that are in the frontier of physics.

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