Study of the 12C excited states above the Hoyle State.

E. López-Saavedra¹, L. Acosta¹, V. Araujo¹, F. Favela¹, A. Huerta¹, J. Aspiazu², G. Murillo², R. Policroniades², P. Santa Rita¹, A. Varela² and E. Chávez¹

1. Instituto de Física, Universidad Nacional Autónoma de México. 04510, Ciudad de México, México.
2. Departamento de Aceleradores, Instituto Nacional de Investigaciones Nucleares, Carretera México-Toluca S/N, La Marquesa Ocoyoacac, 52750, Estado de México, México.

E-mail: eilenslopez.154@gmail.com

Abstract. In this work we study the low-lying excited states of ¹²C, especially above the Hoyle state (0⁺, 7.654 MeV) through the use of the ¹⁴N(d,α)¹²C reaction. The EN-Tandem at ININ delivered deuteron beams between 2.5 and 7.5 MeV. Typical beam intensities were 20-50 nA. Two different compounds were used to produce thin films: Si₃N₄ (150 nm) and of C₅H₅N₅ (10 µm). Angular distributions of emitted α-particles were measured at each energy. The first results of the analysis are presented including quantum number assignments (energy, spin and parity) of the excited states populated.

1. Introduction
The production of the carbón nucleus is a key-step in stellar nucleosynthesis. Its most abundant isotope, ¹²C, is produced through the triple α-process and the short-lived ⁸Be ground state as an intermediate state [1].

The so called “Hoyle state”, the 7.654 MeV 0⁺ in ¹²C, plays an important role in a variety of problems of nuclear astrophysics like the abundance of the elements in the universe and the stellar nucleosynthesis process as a whole. From the nuclear structure point of view, there are unanswered questions regarding its geometry. Even though the standard shell-model approaches and the advanced no-core calculations reproduce many of the ¹²C resonances, they fail to reproduce such excited state [2-10].

Recent experiments report on the measurement of a new high spin (5⁺) state predicted by the Algebraic Cluster Model (ACM). This model predicts other states unseen up to date. So the experimental observation (or not) of these states is crucial in the understanding of the nuclear structure of ¹²C [11-13].

The purpose of this work is to study the nuclear structure of ¹²C by the measurement of the ¹⁴N(d, α)¹²C reaction at different energies between 2.5-7.5 MeV, using two targets the Si₃N₄ and the C₅H₅N₅, the excited states populated are studied, especially those above the Hoyle state (0⁺, 7.654 MeV).

2. Experimental Set-up
Two experiments were performed at the EN-Tandem accelerator of the National Institute of Nuclear Research (ININ). Beams of deuterium between a range of energies of 2.5 and 7.5 MeV were used to bombard two targets: Si₃N₄ (silicon nitride) and C₅H₅N₅ (adenine), in order to study the ¹⁴N(d, α)¹²C
reaction. A detector array of 6 passivated implanted planar silicon (PIPS) detectors was used for the detection of the charged particles. The array was arranged in an angular range between 105°-165°. The detectors were calibrated with beam energies of 2.5, 5.0, 6.5 and 7.0 MeV. The spectra obtained were analysed with the SIMRA software [14].

Angular distributions for each excited state populated in ¹²C were obtained between the beam energy range of 2.5 and 7.5 MeV with 250 keV intervals for a total of 21 runs.

Figure 1 shows the scattering chamber used in the experiments and the arrangement of the detectors.

![Figure 1. Experimental setup used in both experiments, on the left hand side the scattering chamber, on the right hand side, the detector array at backward angles.](image)

### 3. Data Analysis and Preliminary Results

As mentioned above, the SIMRA software was used for the identification of the excited states populated. In Figures 2 and 3 are shown two spectra obtained in the experiments with targets of Si₃N₄ and C₅H₅N₅ respectively.

Despite the resolution obtained for the thin silicon nitride film (70 nm) for the ground state (ω₀), several resonances in ²⁰Si were populated, making ambiguous the identification of the cross section for the reaction of interest.
Because the poor statistics and the presence of other reactions a second target was required, a C_5H_9N target (426μg/cm2), much thicker than the Si_3N_4 film. An example of the spectra obtained in this experiment is shown in Figure 3. Here it was possible to identify several excited states of ^{12}C from the reaction of interest. In addition, we found other reactions that sometimes overlap with those of our interest, these reactions are shown in Figure 3.

In this experiment, the resolution was worse than that in the experiment with Si_3N_4 target, but the statistic were higher. In this experiment we were able to measure the cross sections corresponding to the ground state (0.0 MeV) and the first seven excited states of ^{12}C (4.43 MeV, 7.654 MeV, 9.641 MeV, 10.3 MeV, 10.84 MeV, 11.16 MeV, 11.8 MeV).

In this preliminary work we present experimental angular distributions for the states in ^{12}C with excitation energies of 0.0 MeV, 4.43 MeV, 7.654 MeV and 9.641 MeV respectively, at E_{lab} = 4.25 MeV. A theoretical DWBA calculation (using the DWUCK 4 code [15]) is also shown for each case.
Figure 3. Spectrum obtained in the experiment with C$_5$H$_5$N target, $\theta_{\text{lab}}$: 150°, $E_{\text{lab}}$: 2.75 MeV. In the spectrum the blue boxes correspond to the reaction of interest $^{14}$N (d, a) $^{12}$C, and the excitation energies of the populated states in this spectrum are specified.

3.1 DWBA Analysis and Optical Model Potentials.

The nucleon-nucleus interaction is inherently complicated and the optical model becomes a phenomenological simple model to understand it. Potential and geometrical parameters are adjusted to fit the experimental data to extract information about the nucleus shape and structure.

The optical potential has an imaginary part that takes into account the absorption of the reaction flux from the elastic channel. This is analogous to the scattering and absorption of light by a medium of complex refractive index, which is why it is called the optical model.

Optical potentials obtained through fits of elastic scattering data are widely used to generate the distorted waves used to deduce cross-sections. Such analyses have proved to be a powerful tool in determining nuclear structures [16].

In the Distorted-Wave Born approximation, the relative motion before and after the non-elastic event is described by waves distorted by elastic scattering and its accompanying absorption. Hence this approximation is likely to be valid when the most important single event to take place when two nuclei collide is elastic scattering. Then the others reactions can be treated as perturbations, as weak transitions between elastic scattering states. [17]

Essentially DWBA calculates the cross section to a “pure” single-particle state in independent particular model, in reality, residual interactions mix these states to produce more complex wave functions, so a probability amplitude of a transfer reaction as in our case (d,α) via a particular nlj will
be reduced by a factor $S_{jl}$, called the spectroscopic factor, that reveal how less “pure” than a single-particle state is a measured cross section.

DWBA calculations were performed using the code DWUCK4, with the optical potentials the values provided by V. Gomes Porto [18], they have the following form:

$$V(r) = V_c(r) - V_f(r) - iWg(r)$$

$$f(r) = \frac{1}{1 + \exp \left( \frac{r - R}{a} \right)}$$

$$g(r) = -4a \frac{df(r)}{dr} = \frac{4\exp \left[ \frac{r - R}{a} \right]}{\left( 1 + \exp \left[ \frac{r - R}{a} \right] \right)}$$

Where $V_c$ is the potential due to a uniformly charged sphere, $U$ and $W$ are the depths of the real and imaginary potentials; $f(r)$ and $g(r)$ are Woods-Saxon and its derivative form factors respectively. Figure 4 represent the potentials used in the preliminary results.

**Figure 4.** Optical model potentials used in the DWBA calculations performed.
When nuclear reactions occur, rearrangement of the internal structure of a nucleus will generate states of motion with more energy than the minimum the system can accommodate. These excited states are characterised by their excitation energy, spin, parity, as well as other, often only approximately, good quantum numbers. This rearrangement can easily be visualized as changes in individual nucleon motion, but can also be viewed as changes in bulk motion of the nucleus such as rotation and surface vibration.

Figures 5-8 show the experimental angular distributions obtained compared to the DWBA calculation. In every case the calculation was made twice for two possible angular momentum transfer values. The experimental values are consistent with the theoretical results. In all cases, theoretical results were normalised to the experimental data (no spectroscopic factors).

In further analysis the spectroscopic factors will be calculated.

In the case of the Figure 5, it is easy to see that definitely the transferred angular momentum value is $l=2$, in the results only the value obtained at 125º seems to be out to the DWBA curve.

Figure 5. Angular distribution for ground state (0.0 MeV) in $^{12}$C compared to the preliminary results of the DWBA analysis for $l_{tr}=0$ and $l_{tr}=2$.

In Figure 6 and 7 the angular distributions for the 4.43MeV and the 7.654 MeV excited state are shown respectively, in the case of the first excited state the transferred angular momentum is $l=0$, and for the second state clearly the experimental results coincide with the $l=2$ distribution.
Figure 6. Angular distribution for the 4.43 MeV excited state in $^{12}$C compared to the preliminary results of the DWBA analysis for $l_{tr}=0$ and $l_{tr}=2$.

Figure 7. Angular distribution for Hoyle state (7.654 MeV) compared to the preliminary results of the DWBA analysis for $l_{tr}=0$ and $l_{tr}=2$.

In the 9.641 MeV excited state analysis, our results seem to follow the shape corresponding to an angular momentum transfer of one ($l=1$), except for the data point at 165° which has a value out of the prediction of the DWBA.
Figure 8. Angular distribution for the 9.641MeV excited state in $^{12}$C compared to the preliminary results of the DWBA analysis for $l_{tr}=1$ and $l_{tr}=3$

Table 1 summarizes the quantum numbers assigned after the adenine target experiment.

| Energy (MeV) | $l_{tr}$ | $J^\pi$ |
|-------------|----------|---------|
| 0.0         | 2        | 0+      |
| 4.43        | 0        | 2+      |
| 7.65        | 0        | 0+      |
| 9.64        | 1        | 3-      |

Table 1. Values of transferred angular momentum assigned and the values of $J\pi$ used in the DWBA analysis.

Conclusions
In this work, we presented the preliminary results of the study of some excited states in $^{12}$C performed at the tandem accelerator facility at the National Institute of Nuclear Research; angular distributions were presented and discussed.

Several resonances were found in the experiment with the silicon nitride target and a medium resolution in the peaks of interest was obtained in the experiment with the adenine target.

DWBA calculations were made to compare the predicted angular distribution predictions to the data and be familiar with the process of assigning quantum numbers to the observed states.

At this stage, no attempt was made to deduce spectroscopic factors, this is left as part of our future work.
In order to obtain better data, it would be ideal to perform the next experiment with the supersonic gas jet target (SUGAR) at the 5.5 MV Van de Graaff accelerator at the Physics Institute of the UNAM [19], where a study of the same nuclear reaction was performed recently. In those experiments good statistics and resolution were obtained simultaneously, for both, the low-lying excitation region and the higher region in $^{12}$C, important for understanding the nuclear structure and behaviour of the rotational band of the Hoyle state. Such experiments are planned to occur in the early summer 2017.

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