Yield ratio of neutrons to protons in $^{12}$C(d,n)$^{13}$N and $^{12}$C(d,p)$^{13}$C from 0.6 to 3 MeV

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Abstract The neutron yield in the $^{12}$C(d,n)$^{13}$N reaction and the proton yield in the $^{12}$C(d,p)$^{13}$C reaction have been measured using deuteron beams of energies 0.6–3 MeV. The deuteron beam is delivered from a 4-MeV electrostatic accelerator and bombarded on a thick carbon target. The neutrons are detected at 0°, 24°, and 48° and the protons at 135° in the laboratory frame. Further, the ratio of the neutron yield to the proton yield was calculated. This can be used to effectively recognize the resonances. The resonances are found at 1.4 MeV, 1.7 MeV, and 2.5 MeV in the $^{12}$C(d,p)$^{13}$C reaction, and at 1.6 MeV and 2.7 MeV in the $^{12}$C(d,n)$^{13}$N reaction. The proposed method provides a way to reduce systematic uncertainty and helps confirm more resonances in compound nuclei.

Keywords Proton neutron ratio · $^{12}$C(d,n) · $^{12}$C(d,p) · Trojan horse method (THM)

1 Introduction

The reaction $^{12}$C(p,γ)$^{13}$N has been gaining considerable attention of researchers for both its usefulness as an important reaction to study the properties of light nuclei and the significant role it is expected to play in the cores of main sequence stars and the shells of giant stars [1]. Studying the $^{12}$C(p,γ)$^{13}$N reaction is important to understand the well-known carbon–nitrogen–oxygen cycle (CNO cycle). Reactions occur in the CNO cycle [2] in the following chain: $^{12}$C(p,γ)$^{13}$N(β⁺)$^{13}$C(p,γ)$^{14}$N (p,γ)$^{15}$O (β⁺)$^{15}$N(p,α)$^{12}$C.

The result of the $^{12}$C(d,n)$^{13}$N reaction can be used to study the $^{12}$C(p,γ)$^{13}$N reaction using the Trojan horse method (THM) [3]. Compared with $^{12}$C(p,γ)$^{13}$N, the cross section of $^{12}$C(d,n)$^{13}$N is three times higher with incident...
energy in the order of MeV, making it a better alternative to determine the cross section for $^{12}$C(p,$\gamma$)$^{13}$N. The $^{12}$C(d,n)$^{13}$N reaction can be employed to analyze various materials; in addition, also it can be used as a source of polarized neutrons [4]. The $^{12}$C(d,p)$^{13}$C reaction can be employed in metallurgy and ion beam analysis (IBA) [5]. For example, the properties of steel depend on its carbon content and spatial distribution. The cross section and the resonances of nuclear reactions are highly beneficial in understanding the structure of materials at microlevel [6, 7]. Moreover, deuterated polyethylene (CD$_2$)$_n$ is typically selected as the target for nuclear reactions induced by intensive lasers [8, 9]. At very high plasma temperatures, in addition to the d(d,n)$^3$He reaction, the $^{12}$C(d,n)$^{13}$N reaction could occur. Both these reactions emit neutrons, which may result in a fake enhancement of d(d,n)$^3$He, thereby complicating the measurement. The cross-sectional measurement for $^{12}$C(d,n)$^{13}$N will help clarify the real cross section of d(d,n)$^3$He [10–12] in laser-induced plasma.

The cross sections of the $^{12}$C(d,n)$^{13}$N reaction and the $^{12}$C(d,p)$^{13}$C reaction have been measured in various aspects. The cross section of the $^{12}$C(d,n)$^{13}$N reaction was measured by the neutron detection method using a 4$\pi$ detector [4]. The cross section of the $^{12}$C(d,n)$^{13}$N reaction was measured by counting the $\gamma$-rays from $^{13}$N produced in the reaction [14]. Further, the cross section of the $^{12}$C(d,p)$^{13}$C reaction was measured by counting the $\gamma$-rays [5]. Although much effort has been made, a large diversity of resonances and cross sections exists at approximately 1.4 MeV among the data. In this study, we conduct an experiment to study the ratio between the neutron yield in $^{12}$C(d,n)$^{13}$N and the proton yield in $^{12}$C(d,p)$^{13}$C. This ratio can not only provide information on resonance in the two reactions, but also eliminate the systematic errors caused by the intensity of uncertain incident beam, and it can be applied in thick target reaction systems.

2 Experiment

The experiment was conducted at the Shanghai Institute of Applied Physics, Chinese Academy of Sciences. In this experiment, a deuteron beam of energy 0.6–3 MeV was used to bombard a thick graphite target. Further, the following two reactions were observed in the experiment: $^{12}$C(d,n)$^{13}$N and $^{12}$C(d,p)$^{13}$C. The ratio of the yields of neutrons to protons is extracted.

2.1 Layout of the experiment

Figure 1 shows the schematic of the devices used in the experiment. The target chamber was a cylinder of diameter 60.0 cm. The beam tube transports the deuterium beam from the accelerator to the chamber. Further, three neutron detectors were placed outside the chamber, and a carbon target, Faraday's cup, and proton detector were placed inside the chamber.

The deuteron beam used in the experiment was produced from a 4-MeV electrostatic accelerator. The maximum voltage of the accelerator was set as 3 MeV in this experiment, and the fluctuation of the voltage was less than 2 keV. The beam intensity was about several nA, and three ion beam analysis terminals were present. The experiment was conducted at the 15° terminal; this terminal provides conventional ion beam analysis. Furthermore, a vacuum of 6.2 × 10$^{-5}$ Pa was established.

The graphite target was installed in the center of the chamber, directly facing the deuteron beam. The thickness of the target was 1 mm, which was much larger than the deuteron stopping range of about several $\mu$m, in carbon. The $^{12}$C constitutes 98.93% of the natural graphite used in the experiment.

The Faraday’s cup, which was installed touching the target, was used to count the incident charged particles. However, because the conductivity of the thick graphite target was poor, sparking was unavoidable during the experiment, and it was difficult to estimate the intensity of incident beam. Our method of calculating and analyzing the ratio of neutron yield to proton yield provided a means to study the resonances in the two reactions, even without accurate information about beam intensity.

2.2 Detectors

In the experiment, four detectors were used to count the yields: three EJ-301 detectors for neutrons and one Au–Si
surface barrier detector for protons. The EJ-301 detector was a liquid scintillator detector that is suitable for MeV neutron detection with a good neutron–gamma discrimination. Three EJ-301 detectors were placed at a distance of 112.9 cm from the target at 0°, 24°, and 48° from the beam axis in the experiment. Both the diameter and the thickness of the EJ-301 detectors were 12.7 cm. Further, the solid angles of the three detectors were 1.2 × 10⁻² sr. A time-of-flight (TOF) system based on a Cf-252 neutron source was installed to calibrate the EJ-301 detectors. The efficiency of the neutron detector can be calculated by the ratio of the counts of the neutron detector per second and the theoretical radiation rate. The efficiencies and the emission probabilities of the neutrons from the Cf-252 source follow the Maxwell–Boltzmann distribution. The threshold is applied by the ADC of the neutron signal, i.e., the height of the signal pulse, which is at 300 channels to filter background noise. The efficiency of the EJ-301 detector at 24° varied from different incident energies shown in Fig. 2; the final neutron yields were then corrected by this efficiency.

The Au–Si surface barrier detector was placed at 135 mm from the target at 135° from the beam axis. The diameter of the Au–Si surface barrier detector was 7.5 mm. The solid angle of the Au–Si surface barrier detector was 2.42 × 10⁻³ sr. The efficiency of the Au–Si surface barrier detector was practically 100% for the MeV proton in this experiment.

### 2.3 Methods

\[ Y = \int_0^T \int_0^D I(E, t) N_v \sigma(E) dx dt, \]

where \( D \) is the thickness, \( I(E, t) \) is the incident current, and \( T \) is the time duration of the projectile in the target. Further, \( N_v \) is the atom number per unit volume of the carbon target. And \( \sigma(E) \) is the cross section of the reaction at energy \( E \). The ratio of the neutron yield to the proton one in the two reactions is expressed as follows:

\[ \frac{Y_n}{Y_p} = \frac{\int_0^D I(E) N_v \sigma_n(E) dx}{\int_0^D I(E) N_v \sigma_p(E) dx} \quad (2) \]

Theoretically, a thick target is equivalent to the sum of several continuous thin targets. For example, the yield with an incident energy of 3 MeV can be described as follows.

\[ Y_{\text{total}} = \Delta Y_{0.6} + \Delta Y_{0.7} + \cdots + \Delta Y_{3.0} \quad (3) \]

The thickness of each thin target is the range that the deuteron passes through in the target from energy \( E \) to energy \( E - 0.1 \) MeV. \( \Delta Y_E \) represents the yield of the thin target. The total yield is the sum of yields of all the thin target slices. For the two reactions in our work, when the incident energy is below 0.6 MeV, the cross section is less than 10 mb. Therefore, the slices in which the deuteron energy is less than 0.6 MeV will not be considered. For a very thin target, the formula for yield and cross section of the nuclear reaction is given by,

\[ \Delta Y = I \Delta t N_v \sigma(E) \Delta x. \]

The yield of a thin target is proportional to its cross section. The difference between the ratio of neutron yield to proton yield in the two reactions is given by,

\[
\begin{align*}
Y_{\text{ne}, i+1} &= Y_{\text{ne}} + \Delta Y_{\text{ne}, i+1} \\
\frac{Y_{\text{ne}, i+1}}{Y_{\text{pe}}} &\approx \frac{Y_{\text{ne}}}{Y_{\text{pe}}} - \frac{\Delta Y_{\text{ne}, i+1}}{Y_{\text{pe}}} \\
\end{align*}
\]

Although our ratio values are not continuous, the incident beam energy changes by 0.1 MeV, which is small compared to the resonance width larger than 0.2 MeV in this work. Therefore, Eq. 5 is acceptable. The resonances in the reactions can be identified by an extremely high cross section at a certain energy. If resonance occurs in the reaction at an incident energy \( E \), the yield of the thin target \( \Delta Y_{N_v} \) or \( \Delta Y_{p} \) changes drastically, which may result in a maximum or a minimum value in the ratio. Because the \( \Delta Y \) is proportional to the cross section, the resonances of the two reactions can be identified by the ratios.

### 3 Results

Table 1 lists the deuteron beam current intensity, total charge, beam time, and incident energy used in this work.
The beam time of each run is 5 min, except for the first three runs. In addition, a 2-h background measurement was taken on the EJ-301 detectors without the deuteron beam just before the experiment, which ensured that the background measurements were taken in the same condition.

Figure 3 shows an example of the signals of neutron detector at 48°/C14, when the incident energy is 2 MeV. The pulse shape discrimination (PSD) is calculated to distinguish neutrons and γ-ray. The PSD is given by,

\[
PSD = \frac{Q_I - Q_S}{Q_I},
\]

where \(Q_I\) is the total integral of a whole pulse, and \(Q_S\) is the partial integral from the star of the signal to the point when the signal falls to half the maximum. The different fall times of neutron signals and γ-ray signals in the EJ-301 detector make this method feasible. Neutron signals have a longer attenuation time than γ-ray signals in the neutron detector. The peak in Fig. 3 with higher PSD represents the neutron signals. The threshold of neutron detection is that the ADC of the neutron signals must be larger than 300 channels.

Figure 4 shows an example of the proton signals and the results simulated by SIMNRA at 135°/C14 with an incident energy of 2 MeV. The SIMNRA [19] is software suitable for computer simulation of ion beam analysis methods with MeV ions. The \(Q\) value of this reaction is approximately 2.7 MeV, which helps identify and calibrate protons from the detector. The signals below 1600 channel are the Rutherford backscattered (RBS) deuterons recoiled from the target, and the signals above 2000 channel are protons. The energy distribution of proton is caused by the change in energy of deuteron beam in the thick target. The peak at channel 2774 represents the signals of protons when the incident deuteron energy is 2 MeV. Further, the signals between channel 2774 and channel 3555 belong to the

| Incident energy (MeV) | Time (s) | Current (nA) | Charge (nC) | Incident energy (MeV) | Time (s) | Current (nA) | Charge (nC) |
|-----------------------|----------|-------------|-------------|-----------------------|----------|-------------|-------------|
| 0.600                 | 430      | 1.50        | 676         | 1.900                 | 300      | 0.12        | 36          |
| 0.700                 | 312      | 1.30        | 387         | 2.000                 | 300      | 0.15        | 77          |
| 0.800                 | 296      | 1.00        | 300         | 2.100                 | 300      | 0.10        | 59          |
| 0.900                 | 300      | 1.00        | 295         | 2.200                 | 300      | 0.10        | 59          |
| 1.000                 | 300      | 0.70        | 198         | 2.300                 | 300      | 0.05        | 43          |
| 1.100                 | 300      | 0.50        | 175         | 2.400                 | 300      | 0.07        | 51          |
| 1.200                 | 300      | 0.40        | 120         | 2.500                 | 300      | 0.10        | 92          |
| 1.300                 | 300      | 0.40        | 120         | 2.600                 | 300      | 0.08        | 54          |
| 1.400                 | 300      | 0.20        | 70          | 2.700                 | 300      | 0.07        | 51          |
| 1.500                 | 300      | 0.20        | 70          | 2.800                 | 300      | 0.07        | 51          |
| 1.600                 | 300      | 0.20        | 70          | 2.900                 | 300      | 0.07        | 51          |
| 1.700                 | 300      | 0.20        | 70          | 3.000                 | 300      | 0.07        | 51          |
| 1.800                 | 300      | 0.20        | 48          |                       |          |             |             |
protons produced by an incident energy of less than 2 MeV because of ionization in the thick target. The energy shift is caused by the center of mass motion. The Au–Si detector was placed at 135° in a direction opposite to the beam in the center of mass frame. Under these conditions, the higher the incident energy of the deuteron, the faster the center of mass moves, resulting in low speeds of outgoing protons in the backward direction.

Figure 5 shows the yields of neutrons and protons when the incident energy is between 0.6 and 3 MeV. The yield is corrected by excluding the background and being converted into 300 s. The errors in yields depend on the statistical magnitude. Because every count in each measurement is larger than 560, the errors are less than 4.2%. Because of the sparking of the Faraday’s cup and the imprecise incident beam intensity, the extreme value in the plot does not provide any reasonable conclusion about the cross section of the reactions. Our method enables exclusion of error in the incident beam and finds the physical information in the two reactions.

4 Discussion

The target used in this work is natural graphite, which contains 12C and 13C. The proton and the neutron channels from the reaction between 13C and deuteron must be considered. The cross section of the 13C(d,n)14N reaction is about two to three times larger than that of the 12C(d,n)13N reaction, as indicated by reference [14, 15]. The abundance of 12C is 98.89%, whereas that of 13C is 1.109%. Although the 13C has a larger cross section in this experiment than that of the 12C, the large difference in abundance makes the neutron yield in the 13C target, which is within 3.3% of the total neutron yield, insignificant.

In addition, other possible reaction channels in the experiment, such as 12C(d,n+p)13C, 12C(d,n+d)11C, and 12C(d,n+x)9B, must be considered. The data from the TENDL-2017 Nuclear data library [16] indicate that the cross section of these reactions from 0.6 MeV to 3 MeV is too small to be considered. For the energy range considered in this work, the dominant reactions in this experiment are 12C(d,n)13N and 12C(d,p)13C.

In Fig. 6, the ratio is different in three neutron detection directions because of angular distribution. For low resonance states, the outgoing particles could interfere with each other, as well as with the Coulomb force, resulting in anisotropy. Thus, the ratio in every direction could provide the physical information of nuclear reactions.

The ratio between neutron and proton yields presents some insights into the resonance in 12C(d,n)13N and 12C(d,p)13C. The maximum and the minimum points in the curves in Fig. 6 exhibit some features that indicate the complexity of nuclear reactions.

The minimum points in our curves are attributed to either a sudden jump in proton yield or a sudden drop in neutron yield, as discussed in Methods section. Thus, if the cross section of the neutron does not decrease at the...
resonance points, the cross section of the proton must reach a maximum value, which helps understand the resonance state for the proton channel. Figure 7 shows the cross sections of neutron and proton from Ref. [5, 14, 17]. The plot illustrates whether the cross section of neutron decreases at the possible resonance energies. The possible resonances in Fig. 6 can be checked using these data. The proton detection reported in Ref. [5] was performed at 170°, which is different from our detection. However, because the angular distribution does not influence the resonance recognition, Ref. [5] still works in the following analysis.

For the 12C(d,p)13C reaction, two resonances are found at 1.7 MeV and 2.5 MeV in all directions, and one resonance is found at 1.4 MeV in the 0° direction. In Fig. 7, the cross section of neutron does not decrease at 1.4 MeV, 1.7 MeV, or 2.5 MeV, which guarantees the resonance points for the proton channel. The resonance point at 1.7 MeV originates from the shell in the 14N with an energy of 11.76 MeV [5, 18]. The one at 2.5 MeV originates from the shell in the 14N with an energy of 12.4 MeV [5]. Similarly, the one at 1.4 MeV is consistent with Ref. [5] and originates from the shell in the 14N, whose energy is 11.51 MeV, and spin and parity are 3⁺.

Similarly, for the 12C(d,n)13N reaction, resonances are found at 2.7 MeV at 0° and 24°. Further, two other resonances are found at 1.6 MeV and 1.9 MeV in all directions.

In Fig. 7, the cross section of proton does not increase at 1.6 MeV and 2.7 MeV, which confirms a 1.6-MeV resonance point in 12C(d,n)13N. On the contrary, the cross section at 1.9 MeV decreases significantly, indicating that this minimum value may not be a resonance. The resonance at 2.7 MeV is consistent with that of Refs. [4, 14] originating from the excitation state of 14N with an energy of 12.58 MeV. Further, the resonance at 1.6 MeV in the 12C(d,n)13N reaction originates from the shell in the 14N, whose excitation energy, and spin and parity are 11.66 MeV and 2⁺ or 3⁺, respectively.

Table 2 lists the resonances in 12C(d,n)13N and 12C(d,p)13C reported by Refs. [4, 5, 13, 14, 17, 18] and us.

Figure 6 indicates that the ratio changes rapidly in the lower energy part; however, with the increase in energy, it becomes relatively more stable, making it difficult to recognize the resonance points. Although the yield change rate reflects the cross section, the higher the energy of the incident particles in the thick target, the higher the energy change of deuterons in the entire bombarding process; this leads to a more significant difference between the cross section and the ratio of yield. Under this scenario, only the great resonance points are found in our curves. This is another reason for the fewer number of resonances than in other studies.

| 12C(d,n)13N | 12C(d,p)13C |
|-------------|-------------|
| Reference [14] (MeV) | Reference [4] (MeV) | Reference [17] (MeV) | Reference [13] (MeV) | This work (MeV) | Reference [5] (MeV) | Reference [18] (MeV) | This work (MeV) |
| 0.85 | 0.89 | 0.94 |
| 0.945 | 1.16 | 1.16 | 1.18 |
| 1.279 | 1.3 | 1.31 |
| 1.586 | 1.5 | 1.41 | 1.45 | 1.400 |
| 1.727 | 1.62 | 1.69 | 1.74 | 1.700 |
| 2.279 | 2.32 | 2.45 | 2.500 |
| 2.684 | 2.6 | 2.7 | 2.83 |
5 Summary

In this study, by performing and studying the bombardment of deuterium on a thick carbon target, the resonances in the two reactions, $^{12}\text{C}(\text{d,n})^{13}\text{N}$ and $^{12}\text{C}(\text{d,p})^{13}\text{C}$, were observed. The resonances when the incident deuteron energies were 1.4 MeV, 1.7 MeV, and 2.5 MeV in the $^{12}\text{C}(\text{d,p})^{13}\text{C}$ reaction, and the incident deuteron energies were 1.6 MeV and 2.7 MeV in the $^{12}\text{C}(\text{d,n})^{13}\text{N}$ reaction, were confirmed. We propose the ratio of neutron yield to proton yield as a new means to study the resonances in the $^{12}\text{C}(\text{d,n})^{13}\text{N}$ and the $^{12}\text{C}(\text{d,p})^{13}\text{C}$ reactions. This approach greatly reduces the possible systematic errors arising from both the fluctuation of the incident beam and the complex process of projectile in the thick target.

However, some improvements are necessary in the future, because (a) although both neutron resonance and proton resonance points are found, their numbers are relatively small; (b) the feasibility of this method strongly depends on the incident energy. Moreover, the resonance could be difficult to recognize if the incident energy is very high or the incident energy range is very wide. The corresponding experiments can be improved by the following ways in the future: First, a thin target (approximately 1 µm thick) is recommended to replace a thick target, by which errors arising from the change in deuteron energy in the thick target can be eliminated. Second, the event-by-event method can be applied to eliminate the background signals. This method can be realized by placing a detector to detect the incident beam and performing a coincidence measurement among the incident particles and the outgoing particles. However, as a first step, our method ensures a low systematic error and provides some insights for more precise cross-sectional measurements.

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