S-factor measurement of the $^{13}\text{C}(\text{p},\gamma)^{14}\text{N}$ reaction in reverse kinematics

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Abstract. We measure the S-factor of the $^{13}\text{C}(\text{p},\gamma)^{14}\text{N}$ reaction in reverse kinematics for energies ranging from 561 down to 225 keV with a low background experimental setup. The results are compared with previous measurements and an $R$-matrix treatment is applied to the data in order to obtain the properties of the 511 keV resonance that dominates the cross section at low energies.

1. Introduction

The aim of the nuclear astrophysics is to measure the cross section of the nuclear reactions occurring in the core of the stars, providing thereafter the reaction rates. This work has to be done in optimal conditions because of the very low intensities encountered. In particular, if one is interested in a radiative capture reaction, it consists mainly in decreasing the effect of all background sources that can interact in the photon detector. With this idea, we developed an experimental setup for low background measurements and decided to study proton induced reactions by working in reverse kinematics, suppressing therefore the usual beam induced noise [1]. The first one we studied is the $^{13}\text{C}(\text{p},\gamma)^{14}\text{N}$ reaction that exhibits some astrophysical interest. Indeed, it appears in the CNO cycle and is also, in AGB stars, in competition with the $^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$ reaction, a well-known neutron source for the s-process. Its cross section at low energy is dominated by the 511 keV resonance. Thus, we have measured the de-excitation of this level to the ground state and derived the S-factor. An $R$-matrix treatment has been applied to the data and the results are compared with previous works.

2. Experimental details

The experimental setup presenting the low background conditions has been detailed in a previous paper [1]. Briefly, it consists in a lead castle to reduce the natural radioactivity effects on the high efficiency (133%) germanium gamma-ray detector. An anticoincidence is applied between this detector and a plastic scintillator, placed above the castle, in order to decrease the impact of cosmic rays on the gamma-ray spectra. The setup allows a decrease of 70% of the background interference and provides a sensitivity gain of approximately 200 times between 600 and 3000 keV. A $^{13}\text{C}$ beam was produced by the LARN accelerator, which allows the utilization of nearly all elements of the
periodic table, given that we have worked in reverse kinematics. Moreover, the target used is a hydrogen standard carried out by ion implantation in silicon [2]. It contains about $9 \times 10^{16} \text{H/cm}^2$, as determined with the hydrogen profiles obtained by use of the $^1\text{H}(^{15}\text{N},\alpha\gamma)^{12}\text{C}$ resonant reaction.

We measured the $S$-factor for thirty different energies around the 511 keV resonance up to 561 keV and down to 225 keV, corresponding to energies from 3200 to 7900 keV in the lab system. The effective energy is obtained with the mean energy approximation inside the hydrogen target. Only the gamma-rays from the full-energy (FE) peak were used, being detected at 8.062 MeV (if we neglect the Doppler effect). The only background that has to be subtracted is due to the cosmic-rays. Indeed, thanks to the work in reverse kinematics, no gamma-ray line has appeared above the FE peak. All points were obtained with more than 1000 counts in the ROI, except the two at lower energy (573 and 288 counts). The detection efficiency was obtained by means of MCNPX simulations, corrected with the data of a $^{152}\text{Eu}$ source. The errors take into account the errors on the integrated charge, the number of hydrogen atoms, the detection efficiency and the energy, in addition to the statistical error.

3. Results and discussions
As mentioned before, we focused on the transition from the 511 keV resonant level ($1^-$) to the ground state ($1^+$) of the $^{13}\text{C}(p,\gamma)^{14}\text{N}$ reaction. Though, we measured the branching ratios at the resonance energy for the different transitions from the resonant level. The transition to the ground state has a branching ratio of 0.814. In the following, we assume that this ratio is constant, when it is used. This is an approximation, given the fact that the branching ratio is energy-dependent, as demonstrated in the work of King et al. where they measured all transitions [3]. The energy dependence indicates a decreasing branching ratio, from the resonance towards the low energies, which presents variations between 0.69 and 0.81.

Figure 1. (a) $S$-factor for the $1^-$ to $1^+$ transition of the $^{13}\text{C}(p,\gamma)^{14}\text{N}$ reaction. The results of this work are compared with the data of King et al. [3], Hebbard et al. [4], Hester et al. [5] and Woodbury et al. [6].

Figure 1. (b) Extrapolation of the $R$-matrix fit (circles). Some points of King et al. [3] (squares) are also shown.

Figure 1 (a) presents the $S$-factor that we have obtained and we compare these results with previous measurements. Our data are in good agreement with those of King et al. [3] and of Hebbard et al. [4].
Nevertheless, it seems that they are a little bit lower in intensity, especially at low energy, but also above the resonance. This last point could be explained by a shift of the resonance towards the lower energies and a smaller width. Note that our error bars and those of King et al. (used in NACRE [7]) overlap for nearly all data points, while it is not the case with those of Hebbard et al. that are very small (statistical errors only).

We applied an $R$-matrix treatment to our data in order to derive the properties of the 511 keV resonance and an extrapolation of the S-factor at low energy. As reviewed by Lane and Tomas in 1958 [8], the philosophy of the $R$-matrix theory is to separate the space within two parts, defined by a sphere of radius $a$: an internal one where the nuclear interaction takes place and an external one where only the Coulomb interaction is taken into account. The radius $a$ is of the order of the radius of the colliding nuclei. The treatment consists in deriving an approximate solution of the Schrödinger equation by involving poles in the internal region. These poles are the bound states of the compound nucleus that we want to include in the description of the reaction. It is possible to use only the internal contribution if a strongly bound state is involved.

Figure 1 (b) presents the (extrapolated) fit obtained with $a=6.8\ \text{fm}$ and some points of King et al. [3] are added to show the evolution of the S-factor at higher energy but are not used in the fit. The treatment involved two poles, the 8.062 MeV level ($1^{-}$) and the 8.776 MeV level ($0^{-}$), with no external part. The parameters of the second level were used as fixed parameters, taken from Ajzenberg-Selove [9]. The fit to our experimental data is very good, providing a $\chi^2=0.14$. Moreover, the extrapolation at higher energy is pretty good, in comparison with the data of King et al., except above 800 keV where the contribution of the second resonance starts to dominate (the data in Figure 1 are only for the transition to the ground state).

| $E_0$ (keV) | $\Gamma_R$ (keV) | $\omega_\gamma$ (eV) |
|------------|----------------|---------------------|
| This work  | 511.3±0.5      | 34.5±1.1            |
| Seagrave [10] | ~511          | 30.2±0.9            |
| Hebbard [4] | 511±4         | 30±2                |
| Milne [11]  | ~511           | ~33                 |
| Ajzenberg-Selove [9] | 512±1 | 30±1               |
| King [3]    | 517.8±0.5     | 40±1                |
| Galster [12] | 511.5±1.2   | 33.8±1.2            |

Table 1. Comparison of the results for the 511 keV resonance obtained with the $R$-matrix method ($a=6.8\ \text{fm}$) with those of the literature.

The properties of the 8.062 MeV level are compared to the literature in Table 1. In 1991, Galster et al. [10] published a review of existing values (Seagrave [11], Hebbard et al. [4], Milne [12] and Ajzenberg-Selove [9]) and provided some average values that, in addition, took into account measurements done in their work. The resonance energy is in very good agreement with the previous measurements, except with King et al., as already pointed out before. The resonance width is close to the one of Galster et al. The total resonance strength is too low. That one is evaluated from the resonance strength of the studied transition, taking into account the measured branching ratio. In fact, it is not clear if the resonance strength presented in the literature is the observed or the calculated one, as introduced by Lane and Thomas [8]. The one given in this work is the observed one, while the calculated one is about 20% higher, which could reduce the discrepancy.

Finally, we derived extrapolated S-factor values at low energy. For the transition to the ground state, we get $S(0) = 3.94±0.59\ \text{keV.b}$ which is lower than $S(0) = 5.16±0.72\ \text{keV.b}$ that Mukhamedzhanov et al. [13] obtained from a $R$-matrix fit to the data of King et al. [3]. However, they
are consistent within the error bars. If we consider the total S-factor (with the approximation of the constant branching ratio) we have \( S(0) = 4.85 \pm 0.76 \text{ keV.b} \) and \( S(25 \text{ keV}) = 5.12 \pm 0.80 \text{ keV.b} \) which is still lower than \( S(0) = 7.60 \pm 1.10 \text{ keV.b} \) and \( S(25 \text{ keV}) = 8.0 \pm 1.2 \text{ keV.b} \) from Mukhamedzhanov et al. But our value is near the \( S(0) = 5.7 \pm 0.8 \text{ keV.b} \) of Hebbard et al. [4].

4. Conclusions and perspectives

We measured the S-factor of the \(^{13}\text{C(p,}\gamma)^{14}\text{N}\) reaction between 225 and 561 keV and fitted the data with the \( R\)-matrix technique. This measurement was made possible by a low background setup and the work in reverse kinematics. This technique provides very clean measurements and we suggest applying it in underground facilities, which could allow the study of more difficult reactions. In particular, the \(^{15}\text{N(p,}\gamma)^{16}\text{O}\) reaction for which the recent S-factor measurement by Bemmerer et al. [14] presents relatively high error bars mainly because of the interaction between the proton beam and the boron contaminants.

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