Revised Cross Section of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction between 5 and 8 MeV

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As suggested in a Comment by Peters, Phys. Rev. C 96, 029801 (2017), a correction is applied to the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ data of Harissopulos et al., Phys. Rev. C 72, 062801(R) (2005). The correction refers to the energy-dependent efficiency of the neutron detector and appears only above the $(\alpha,n_1)$ threshold of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction at about $E_\alpha \approx 5$ MeV. The corrected data are lower than the original data by almost a factor of two. The correction method is verified using recent neutron spectroscopy data and data from the reverse $^{16}\text{O}(n,\alpha)^{13}\text{C}$ reaction.

I. INTRODUCTION

The $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction plays an important role in nuclear physics and astrophysics. Many conventional nuclear physics experiments suffer from background which is produced by the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction in carbon buildup on the target although $^{13}\text{C}$ has only a small natural abundance of about 1%. In addition, the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction may be relevant as radiogenic neutron background in underground laboratories (e.g., [1–3]). Here typical primary energies $E_\alpha$ vary between about 5 and 9 MeV for the uranium and thorium decay chains. As the $(\alpha,n)$ cross section decreases strongly towards low energies, the relevant thick-target yield is essentially defined by the $(\alpha,n)$ cross section close and slightly below the primary $E_\alpha$, i.e. between about 5 and 8 MeV. (All energies are given as laboratory energies $E_\alpha$,lab or $E_n$,lab throughout this paper; exceptions are explicitly stated.)

Unfortunately, this energy range above 5 MeV is not well-studied in literature. Much work has been done to measure the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ cross section at very low energies. This energy range is important to determine the stellar $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction rate which defines the strength of the main neutron source for the astrophysical s-process. The various experimental data sets in the low MeV region [6–12] agree reasonably well, as e.g. discussed in the NACRE compilations [13, 14] and in a recent review [15].

The experimental data by Harissopulos et al. [7] (hereafter: Har05) extend the low MeV region up to about 8 MeV and are thus the only experimental basis for the determination of radiogenic neutron yields from the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction. However, these Har05 data have been questioned severely in a recent Comment by Peters [16]. There it is stated that “the actual cross section above 5 MeV could be almost 50% lower than reported by Harissopulos et al.”, and it is pointed out that there is a problem with the neutron detection efficiency in the Har05 data. It is the aim of the present study to further investigate the Har05 data above 5 MeV and to provide a reliable correction to these experimental data.

II. RE-ANALYSIS OF THE HAR05 DATA

The Har05 experiment used a 4π thermal $^3\text{He}$ neutron detector, embedded in a cylindric polyethylene moderator. The determination of the neutron efficiency $\eta$ for such a detector is a complicated problem because $\eta$ depends on the neutron energy. However, this information is lost because of the thermalization of the neutrons in the moderator. It is worth noting that similar problems with the neutron efficiency have been identified in a series of $(\gamma,n)$ experiments, performed at Livermore and Saclay; a correction to these $(\gamma,n)$ data was recently provided (e.g., [17]). The present study follows the idea of [17] to provide improved data from a combination of experimental and theoretical information.

In Har05, the neutron efficiency $\eta$ was determined as a function of the neutron energy $E_n$ (in MeV) in their Eq. (1) from 2 to 9 MeV. It is stated that $\eta$ varies between 31% at $E_\alpha = 0.8$ MeV and 16% at $E_\alpha = 8.0$ MeV. As pointed out by Peters [16], the low efficiency $\eta$ at $E_\alpha = 8$ MeV indicates that Har05 assumed that the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction is governed by the $(\alpha,n_1)$ channel, leading to relatively high neutron energies. However, slightly above $E_\alpha \approx 5$ MeV the $(\alpha,n_1)$, $(\alpha,n_2)$, $(\alpha,n_3)$, and $(\alpha,n_4)$ channels open, and depending on the branching, the average neutron energy $E_n$ is significantly lower and the effective neutron detection efficiency $\eta_{\text{eff}}$ is significantly higher than assumed in Har05. Thus, instead of using the efficiency $\eta_0$ for the $(\alpha,n_1)$ channel, an effective efficiency $\eta_{\text{eff}}$ has to be used where the $b_j$ are the neutron branchings of the $(\alpha,n_1)$ channel at a given $E_\alpha$, and the $\eta_j$ are the energy-dependent detection efficiencies for neutrons from the $(\alpha,n_j)$ channel. For the energy range under study in Har05, the sum in Eq. (1) runs over the $^{16}\text{O}$ 0+ ground state ($j = 0$) and the excited states at $E_\alpha = 6049$ keV (0+), $6130$ keV (3−), $6917$ keV (2+), and $7117$ keV (1−).

Finally, this leads to a correction factor $f_{\text{corr}}$ for the Har95 cross section data:

$$f_{\text{corr}} = \frac{\eta_0}{\eta_{\text{eff}}}$$

(2)
Obviously, the correction factor is $f_{\text{corr}} = 1.0$ for energies below 5 MeV, and thus the agreement of the Har05 data with other literature data at low energies is not affected by the present correction. For a vanishing $(\alpha,n_0)$ contribution (and thus low neutron energies around $E_\alpha \approx 8$ MeV) the correction factor will approach its lower limit $f_{\text{corr}} \approx 0.5$ which results from the given efficiency limits of 51% at low and 16% at high neutron energies in Eq. (1) of Har05.

The present study uses the TALYS code [18, 19] to calculate the branching ratios $b_j$ of the $(\alpha,n_j)$ channels. Of course, such a statistical model approach can only be valid on average, and individual resonances in the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction may show a completely different decay branching. But it has been shown recently that a careful selection of TALYS parameters allows to reproduce $(\alpha,n)$ cross sections for intermediate [20, 21] and even light nuclei [22], at least at energies $E_\alpha$ above a few MeV. The calculated branching ratios $b_j$ as a function of energy $E_\alpha$ are shown in Fig. 1. The correction factor $f_{\text{corr}}$ is then calculated from Eqs. (1) and (2) using the energy-dependent efficiencies $\eta_j$ from Eq. (1) of Har05 and the neutron energies $E_{n,j}$ of the $(\alpha,n_j)$ channels from reaction kinematics. $f_{\text{corr}}$ is also shown in Fig. 1. All numbers (Har05 cross sections, calculated branching ratios $b_j$, efficiencies $\eta_0$ and $\eta_{\text{eff}}$, correction factor $f_{\text{corr}}$, and the corrected cross sections) are provided as Supplemental Material to this study [23].

The original cross sections of Har05 are shown in Fig. 2 as dots; the larger diamonds show the corrected data using $f_{\text{corr}}$ from Eq. (2) and Fig. 1. Further details of Fig. 2 are discussed in the following Sect. III.

FIG. 1. (Color online) Branching ratios $b_j$ for the $(\alpha,n_j)$ channels of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction as a function of energy $E_\alpha$ (lower part a) and resulting correction factor $f_{\text{corr}}$ from Eq. (2) for the cross sections of Har05 (upper part b).

FIG. 2. (Color online) Cross section of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction. The corrected data (blue diamonds) are significantly lower than the original Har05 data (lightblue dots) for energies above the opening of the $(\alpha,n_1)$ channel at $E_\alpha \approx 5$ MeV. The new estimated $(\alpha,n_0)$ cross sections (red triangles) are close to the results which are obtained from the reverse $^{16}\text{O}(n,\alpha)^{13}\text{C}$ reaction (orange stars and green squares). Further discussion see text.

III. DISCUSSION

Up to now, a statistical model calculation (using TALYS) was applied to correct the experimental data of Har05. Fortunately, there are two ways to verify the calculations and the applied correction factor $f_{\text{corr}}$.

The first check uses the recently measured branching ratios $b_j$ by Febbraro et al. [24]. Here a deuterated scintillator was used for neutron spectroscopy, and it was possible to unfold the light response of the scintillator to derive the neutron energies in the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction at $E_\alpha = 7.5$ MeV (see Fig. 8 of [24]). It is found that the $(\alpha,n_2)$ channel dominates which populates the 3− state in $^{16}\text{O}$ at 6130 keV. The $(\alpha,n_0)$ ground state and $(\alpha,n_2) 2^+$ (6917 keV) contributions are about a factor of four smaller. Although no absolute efficiency calibration was applied in [24], the TALYS calculation nicely reproduces the trend with a dominating $(\alpha,n_2)$ channel (46%), weaker $(\alpha,n_0)$ (20%) and $(\alpha,n_3)$ (19%) channels, and minor contributions from the $(\alpha,n_4)$ (6%) and $(\alpha,n_1)$ (9%) channels at $E_\alpha = 7.5$ MeV.

The measured branching ratios $b_j$ of [24] clearly exclude the assumption in Har05 that the $(\alpha,n_0)$ channel is dominating, and it results that the neutron energies are much lower than assumed in Har05. Consequently, the correction factor $f_{\text{corr}}$ in Eq. (2) and Fig. 1 is confirmed.

A second test can be made using experimental data from the reverse $^{16}\text{O}(n,\alpha)^{13}\text{C}$ reaction. The
The relevant energy range is covered by the \((n,\alpha)\) cross section by Khryakov et al. \[25\] and Giorginis et al. \[26\] (as provided by EXFOR \[27\], including a correction to the presented data in Fig. 8 of \[28\]). After conversion from \((n,\alpha)\) cross sections to \((\alpha,n)\) cross sections, the data of \[25\] and \[26\] are also included in Fig. 2.

As expected, at low energies below the opening of the \((\alpha,n_1)\) channel, the converted \((n,\alpha)\) data agree well with the \((\alpha,n_0)\) data of Har05. However, at higher energies the converted \((n,\alpha)\) data are significantly lower than the Har05 data, reaching a discrepancy up to about one order of magnitude at energies around 7 – 8 MeV. This finding again invalidates the approach by Har05 that the \((\alpha,n_0)\) channel is dominating.

An attempt is made to estimate the \((\alpha,n_0)\) cross section from the corrected Har05 data and the calculated ground state branching \(b_0\) (red triangles in Fig. 4). These estimated \((\alpha,n_0)\) data are close to the converted \((n,\alpha)\) data of \[22\] (green squares). At energies above 6 MeV, the estimated data are still slightly higher than the converted \((n,\alpha)\) data; this can be interpreted as evidence that most of the resonances in the \((\alpha,n)\) data at higher energies preferentially decay to excited states in \(^{16}\text{O}\), but not to the \(^{16}\text{O}\) ground state.

Both above methods of verification confirm that the TALYS calculation of the ground state branching is realistic with a trend that the real ground state branching may be even lower than the calculated 30% – 15% above 6.5 MeV. Thus, it becomes obvious that a correction to the Har05 data has to be applied where a ground state branching \(b_0 = 1.0\) was assumed. A correction factor \(f\text{corr} \approx 0.65 – 0.55\) is determined above \(E_\alpha \approx 6.5\) MeV, with a lower limit of about 0.5 (for a vanishing ground state branching \(b_0\) and thus low neutron energies \(E_\alpha\)). This leads to an uncertainty of the correction factor \(f\text{corr}\) of the order of 10% – 20%. This result is almost independent of details of the \(b_j (j \neq 0)\) branching ratios towards excited states in \(^{16}\text{O}\) because only the \((\alpha,n_0)\) channel leads to neutrons with relatively high energies. The uncertainty of \(\eta\text{eff}\) and \(f\text{corr}\) may be somewhat larger close above the respective \((\alpha,n_j)\) thresholds where the neutron emission in the laboratory is kinematically focused to forward directions.

The uncertainty of the correction factor \(f\text{corr}\) is explained in more detail for the energies of 6 MeV and 7.5 MeV, i.e. relatively close above the threshold of the \((\alpha,n_1)\) channel and at the energy of the new experimental data of \[22\]. At 6 MeV, the calculated branching ratios are \(b_0 = 0.48\), \(b_1 = 0.09\), and \(b_2 = 0.43\), leading to an effective efficiency \(\eta\text{eff} = 29.4%\) instead of \(\eta_0 = 20.4%\). The uncertainty of the calculated ground state branching \(b_0\) is carefully assumed with a factor of two. This leads to an upper limit of \(b_0 \approx 1\) and to a lower limit \(b_0 = 0.24\). Obviously, for the upper limit of \(b_0\) I find \(\eta\text{eff} = 21.0% \approx \eta_0\). The lower limit of \(b_0\) results in an increased \(\eta\text{eff} = 33.6%\). Consequently, \(f\text{corr} = 0.695 \pm 0.087\).

At 7.5 MeV, the corresponding numbers are \(b_0 = 0.20\), \(b_1 = 0.06\), \(b_2 = 0.46\), \(b_3 = 0.19\), and \(b_4 = 0.09\), leading \(\eta\text{eff} = 31.4%\) instead of \(\eta_0 = 18.2%\). The upper and lower limits of \(b_0\) (again assuming a factor of two uncertainty for \(b_0\)) result in a range of \(\eta\text{eff}\) between 28.4% and 33.0% and \(f\text{corr} = 0.580\pm 0.062\). Summarizing, even the assumed significant uncertainty of a factor of 2 for the ground state branching \(b_0\) translates to a typical uncertainty of the correction factor \(f\text{corr}\) of the order of 10 – 20%. Note that this result is almost independent on the detailed branching towards the 4 excited states because the excitation energies are within about 1 MeV, and thus the neutron energies are low and very similar for all branchings \(b_1\), \(b_2\), \(b_3\), and \(b_4\).

Of course, these uncertainties should be considered as average uncertainties, i.e. uncertainties of the average cross sections over a significant energy interval. Individual resonances (as visible in Fig. 2) may show a completely different branching than calculated by TALYS. In the extreme case of a resonance with a full ground state branching \(b_0 = 1.0\), the correction factor \(f\text{corr} = 1.0\) remains unity within the energy interval of this resonance. Thus it is not meaningful to provide uncertainties for each data point of the corrected Har05 data. Instead, an overall uncertainty of about 15% is recommended for yield calculations which average over a sufficiently wide energy interval of at least a few hundred keV.

In principle, the experimental approach of Har05 can also be used to provide at least a rough estimate of the neutron energy via the so-called “ring ratio”: the ratio of the neutron yields in the outer and inner ring of the Har05 neutron detector depends on the neutron energy. Unfortunately, the experimental setup of Har05 used only one ADC for the sum signal of all neutron detectors, and thus no ring ratio can be provided from the Har05 experiment \[28\].

It is also interesting to see that in general the statistical model calculation provides a reasonable agreement (on average) with the experimental \(^{13}\text{C}(\alpha,p)\)\(^{14}\text{O}\) data (see Fig. 4). However, the calculation clearly overestimates the experimental data around \(E_\alpha \approx 3.5 – 5\) MeV. This energy interval shows a relatively small number of resonances, compared to lower and higher energies. It is not surprising that the agreement between the statistical model calculation and the experimental data becomes better in regions with a higher number of resonances, but even at the highest energies under study between 6 and 8 MeV the calculation is slightly higher than the average of the experimental data. The overestimation of the experimental cross sections in the statistical model does not affect the correction factor \(f\text{corr}\) which depends only on the calculated branching ratios \(b_j\). Interestingly, a similar overestimation for the TALYS calculation is also found for new preliminary data of the \(^{13}\text{N}(\alpha,p)\)\(^{16}\text{O}\) mirror reaction \[29\].

Finally, a brief comparison to R-matrix fits from literature \[6, 30\] is provided. The fit by Heil et al. \[4\] did not include the Har05 data, but was constrained by \((n,\alpha)\)
data up to neutron energies of 8.5 MeV. Above about $E_n = 5$ MeV, the fit of the $(\alpha,n)$ data in Fig. 17 of [4] is lower than the Har05 data whereas the fit agrees with the Har05 data at lower energies. This result is consistent with the findings of the present study. The later study by Kunieda et al. [30] uses the Har05 data for fitting. But unfortunately this study focuses on the low-energy region with $E_n < 4.6$ MeV, and no conclusion can be drawn from $\alpha(C,n)$ for the energy range under study in this work.

IV. CONCLUSIONS

The $^{13}\text{C}(\alpha,n)^{16}\text{O}$ data of Harissopulos et al. [7] cover a wide energy range from about 0.8 MeV to 8 MeV. At low energies below the opening of the $(\alpha,n_1)$ channel at about 5 MeV, these data agree well with various literature data. The cross sections between 5 MeV and 8 MeV are important for the estimate of radiogenic neutron background in low-background environments like underground laboratories. In this energy range experimental data are rare, and the experimental data by Harissopulos et al. have been questioned in a Comment by Peters [16].

Following the criticism by Peters, the present study provides a correction to the experimental data which is based on an improved determination of the neutron detection efficiency $\eta_d$. Whereas the original study of Harissopulos et al. assumed a dominating $(\alpha,n_0)$ ground state contribution (with resulting high neutron energies and low detection efficiency), the present work finds a dominating $(\alpha,n_2)$ channel, populating the $3^-$ state in $^{16}\text{O}$ (with resulting lower neutron energies and higher detection efficiency). The derived correction factor $f_{\text{corr}}$ decreases from unity at the opening of the $(\alpha,n_1)$ channel at $E_n \approx 5$ MeV down to about 0.55 at $E_n \approx 8$ MeV. The applied method and the resulting $f_{\text{corr}}$ are validated by further studies which are based on recent neutron spectroscopy data [23] and on data from the reverse $^{16}\text{O}(n,\alpha)^{13}\text{C}$ reaction [23, 24]. The corrected $^{13}\text{C}(\alpha,n)^{16}\text{O}$ cross sections are reliable with uncertainties of about 15%. A further reduction of uncertainties requires new experiments which should use improved neutron detectors, either with spectroscopic properties [24] or with almost flat detection efficiency (as e.g. suggested in [31]).

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