Measurement of the ^{13}C$(\alpha, n_0)^{16}$O differential cross section from 0.8 to 6.5 MeV

R.J. deBoer,[1,*] M. Febbraro,[2] D.W. Bardayan,[1] C. Boomershine,[1] K. Brandenburg,[3] C. Brune,[3] S. Coil,[1] J. Derkin,[3] S. Dede,[1] F. Fang,[1] A. Fritsch,[4] A. Gula,[1] Gy. Gyürky,[5] B. Hackett,[6] G. Hamad,[3] Y. Jones-Alberty,[3] R. Kelmar,[1] K. Manukyan,[1] M. Matney,[1] J. McDonaugh,[1] Z. Meisel,[3] S. Moylan,[1] J. Nattress,[2] D. Odell,[3] P. O'Malley,[1] D. Robertson,[1] Shahina,[1] N. Singh,[3] K. Smith,[7] M.S. Smith,[2] E. Stech,[1] W. Tan,[1] and M. Wiescher[1]

[1]*Department of Physics and Astronomy, University of Notre Dame, Notre Dame, Indiana 46556 USA*
[2]*Oak Ridge National Laboratory, Oak Ridge, TN 37831*
[3]*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA*
[4]*Department of Physics, Gonzaga University, Spokane, Washington 99258, USA*
[5]*Institute for Nuclear Research (Atomki), P.O.B 51, H-4001 Debrecen, Hungary*
[6]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[7]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

(Dated: February 28, 2023)

The cross section of the ^{13}C$(\alpha, n_0)^{16}$O reaction is needed for nuclear astrophysics and applications to a precision of 10% or better. Yet inconsistencies among 50 years of experimental studies currently lead to an uncertainty of ≈15%. Using a tate-of-the-art neutron detector array, we have performed a high resolution differential cross section study covering a broad energy range. These measurements result in a dramatic improvement in the extrapolation of the cross section to stellar energies potentially reducing the uncertainty to ≈5% and resolving long standing discrepancies in higher energy data.

I. INTRODUCTION

The ^{13}C$(\alpha, n_0)^{16}$O reaction, or its time reverse ^{16}O$(n, \alpha_0)^{13}$C reaction, is an important quantity for many different aspects and applications in nuclear physics. Namely in the field of nuclear astrophysics, the low-energy cross section of the ^{13}C$(\alpha, n)^{16}$O reaction determines the neutron production in a variety of stellar environments and is therefore a critical parameter for modeling the chemical evolution of our universe.

In Asymptotic Giant Branch (AGB) stars, the mixing of hydrogen into the helium burning shell of the star triggers the ^{12}C$(p, \gamma)^{13}$N$(\beta^+\nu)^{13}$C reaction sequence towards the production of ^{13}C, which by subsequent α-capture feeds the ^{13}C$(\alpha, n)^{16}$O reaction. The strength of the neutron source mechanism depends on the hydrodynamic intershell mixing conditions, the so-called carbon bubble - and the strength of the reaction, which is determined by the complex nature of the low energy reaction cross section. This neutron source determines the neutron flux for the slow-neutron-capture or s-process, which is responsible for approximately half of the heavy, naturally occurring, elements up to the lead-bismuth region [1]. The low energy cross section is not only important for determining the strength, but is also essential for providing a critical parameter for a reliable modeling of the neutron production site in the AGB star environment through the analysis of the abundance distribution of s-process elements [2]. The experimental study and extrapolation of the reaction cross section over a wide stellar energy range has therefore been one of the flagship studies for underground accelerator facilities [3, 4].

The cross section towards higher energies plays an important role at the on-set of chemical evolution in the early phase of our universe. The reaction cross section determines the neutron flux for the intermediate neutron capture or i-process in very old stars, the Carbon Enhanced Metal Poor (CEMP) stars [5], where the neutron production occurs in a deep, convective, hot, environment in which ^{13}N is mixed into the hotter regions of the hydrogen burning shell before its decay, and the subsequent ^{13}C$(\alpha, n)^{16}$O reaction occurs at much higher temperatures [6, 7]. The enhanced neutron production generates a substantially higher neutron flux, that drives the neutron capture reaction path away from stability, generating a unique abundance distribution pattern, as observed in CEMP stars [8]. Again a reliable set of reaction cross section data is essential in order to compare the observed with predicted i-process abundance pattern as well as study the deep convection conditions in such environments.

In large scale neutrino detectors such as the Kamioka Liquid Scintillator Antineutrino Detector (KamLAND), the ^{13}C$(\alpha, n)^{16}$O reaction has been identified as the main background source, competing with signals from geo-neutrinos, in the determination of the neutrino mix-

* rdeboer1@nd.edu

ing $\nu_1 - \nu_2$ [9, 10]. The reaction is induced by higher energy α-particles released through the natural decay chains in impurities in the liquid scintillator material. The background therefore depends critically not only on the actinide impurities, but also on the neutron branching in the decay channel. There are two ways the ^{13}C$(\alpha, n)^{16}$O reaction can mimic these interactions. First, through the production of high energy neutrons from the ^{13}C$(\alpha, n_0)^{16}$O that elastically scatter on ^{12}C producing a prompt γ-ray followed by a neutron capture. The second way is through the ^{13}C$(\alpha, n_1)^{16}$O reaction to the 6050 keV final bound state [11, 12]. In that case, the $E0$ decay, $e+/e-$ followed by neutron capture, is indistinguishable from inverse β-decay. Therefore, probing the reaction over a wide energy range is essential in order to characterize the contributions of the various decay channels.

Additionally, neutron transport simulations play an important role in the nuclear energy sector. These simulations are based on cross section evaluations like ENDF/B, where the ^{16}O$(n, \alpha)^{13}$C reaction is placed at high priority [13, 14]. These transport simulations are necessary to estimate the flux of neutrons traversing from reactor or other neutron environments, to determine the energy distribution and calculate the shielding and moderator requirements. Monte-Carlo simulations of neutron transport are critical in studying the response of neutron detectors employed in low-, intermediate-, and high- energy physics, as well as for estimating the activity induced in different detectors by intense neutron fields. The latter is an important aspect for neutron dosimetry.

For all these purposes this experimental study and analysis of the low energy ^{13}C$(\alpha, n_0)^{16}$O reaction is essential. This paper presents new, comprehensive, differential cross section measurements, made using a state-of-the-art detector array and analyzed using a comprehensive R-matrix analysis with Bayesian uncertainty estimation. Nearly all past experimental studies have been measurements of the angle integrated neutron cross section through detection of thermalized neutrons using "4π" moderator counters [15–18]. This type of measurement technique can be advantageous because of the high neutron detection efficiency, and, in principle, insensitivity to the underlying angular distributions of the outgoing neutrons. However, these types of measurements must be done with great care, as the above advantages can also be drawbacks. With no sensitivity to the energy of the outgoing neutrons, yields from background reactions are more difficult to identify. If the detector does not have an efficiency that is independent of neutron energy, conversion of the observed yield to cross section also requires the branching ratio to different final states, which is often not available. Finally, modern detector simulations have revealed that the moderator sizes of many "4π" detectors are insufficiently large to result in detection yields that are independent of the underlying angular distributions, especially when used for the measurement of higher energy neutrons. The underlying angular distributions are often unknown, and thus the yields can not be accurately corrected. In addition, all of these types of detectors suffer from some loss of efficiency at very forward and backward angles where the beam pipe must pass through the moderator. These issues have been discussed in detail in the recent works of Peters [19] and Mohr [20].

Further, the measurements of Harissopulos *et al.* [18] significantly underestimated their uncertainties due to the above effects, causing inconsistencies to develop between ENDF/B-VII.1 and ENDF/B-VIII.0 evaluations [14, 21] for the ^{16}O$(n, \alpha)^{13}$C reaction. First, and most significant, the absolute scale of the cross section was underestimated by ≈30%, yet the total systematic uncertainty was quoted as 3%. Taken at face value, this very small systematic uncertainty resulted in a large weighting of this data set in the global R-matrix evaluation. Second, the compact design of the detector was insufficient to achieve a uniform neutron detection efficiency relative to the beam energy and neutron emittance angle. This resulted in inconsistent yields between resonances with differing underlying angular distributions, leading to energy dependent inconsistencies in the shape of the cross section as well. Again, relative uncertainty was vastly underestimated at 2%, while later investigations have shown the effect to be as large as 20%. Further, at energies above the threshold, where excited states can be populated in the ^{16}O final state, the assumption that the ground state transition dominates the total reaction cross section has proven to be incorrect [11, 12, 22], again resulting in an up to 20% error in the calculation of the total reaction cross section [19, 20].

In order to resolve these discrepancies, the experimental measurements presented here were performed at the University of Notre Dame (UND) Nuclear Science Laboratory (NSL) using the 5 MV Stable ion Accelerator for Nuclear Astrophysics (St. ANA) [23]. Singly and doubly ionized He beams were produced over a laboratory energy range from $E_\alpha = 0.8$ to 6.5 MeV with typical beam intensities of ≈10 $e\mu$A on target. Targets were fabricated at the Institute for Nuclear Research (ATOMKI) in Debrecen, Hungary. Enriched (99%) ^{13}C powder was evaporated onto a 0.5 mm Ta backing, which also served as a beam stop, creating a thin layered target of 10.3(6) μg/cm^2. The target thickness was determined precisely by measuring the thick target energy loss over the narrow resonance in the ^{13}C$(\alpha, n)^{16}$O reaction at $E_\alpha = 1.05$ MeV. To mitigate deterioration from beam heating, the target backing was water cooled throughout the experiment and the beam was rastered over the target area. A liquid-nitrogen cooled and electrically isolated copper pipe, that was biased to −300 V, was placed in the target chamber to serve as both a cold trap and electron suppressor.

This reference target was used to perform the majority of the measurements and no difference in yield was observed after ≈0.8 C of accumulated charge. A target of half this thickness was utilized to scan over narrow resonances in order to reduce the distortion to the cross

section from energy averaging effects. After ≈0.46 C of accumulated charge, the target's yield was found to degrade by ≈15%. At the lowest energies, two additional targets of the same thickness were used for measurements below ≈1 MeV. For these targets, beam intensities up to 50 μA were utilized resulting in up to 1.7 C of accumulated charge with no observable degradation. The targets were very similar to those used by the recent measurements of ^{13}C$(\alpha,n)^{16}$O at LUNA as reported in Ciani *et al.* [24].

Differential cross sections were measured using the Oak Ridge national laboratory Deuterated Spectroscopic Array (ODeSA) [25], which has been used for several previous studies [11, 26, 27]. The array consisted of nine deuterated scintillators mounted on a swing arm. For most energies, the swing arm was rotated to two different positions, with an offset of 7.5°, in order to obtain 18 point angular distributions between 0 and 157.5°. The response matrix for ODeSA [25] was measured at the Edwards Accelerator Laboratory at Ohio University using time-of-flight and the well known ^{9}Be$(d,n)^{10}$B thick-target neutron yield [28], which was determined relative to measurements with a ^{235}U fission chamber [29]. The ^{13}C$(\alpha,n)^{16}$O measurements at the UND NSL could thus be made using a direct current beam, substantially decreasing run times through the use of higher beam intensities and simplified beam preparation without bunching. Neutron spectroscopy was then accomplished using the calibrated detector response matrix and a light response unfolding algorithm [30, 31].

Because of the positive Q-value of the ^{13}C$(\alpha,n_0)^{16}$O (+2.2 MeV) reaction, this method was especially well suited, able to achieve better spectral resolution than time-of-flight for the target-to-detector distance of 30 cm [31]. The Ta backing produced very little yield from other background reactions with no measurable background at the neutron energies of the ^{13}C$(\alpha,n_0)^{16}$O reaction. The only background peaks observed came from the ^{19}F$(\alpha,n)^{22}$Ne reaction at energies in excess of $E_\alpha \approx 3$ MeV, but owing to its negative Q-value ($Q = -1.95$ MeV), neutrons from this reaction were well separated from those of the ^{13}C$(\alpha,n_0)^{16}$O reaction by ≈5 MeV, easily distinguishable with the ≈4% energy resolution achieved through the spectrum unfolding. Above $E_\alpha \approx 5$ MeV, excited states can be accessed in the ^{16}O final state, these are again very well separated from those of the ground state. However, because the excited states are closely spaced in energy and overlap with yields from the ^{19}F$(\alpha,n)^{22}$Ne background, the yields of these excited state reactions were not extracted.

The most significant corrections to the experimental yields in the conversion to absolute differential cross sections came from the neutron scattering on the target backing, holder, and other beam components very close to the target. These in and out scattering corrections were simulated using `MCNP6` [32], where a detailed model of the setup was created. These corrections were most significant around 0 and 90°, where corrections to the yield of up to 30% were required. However, for the other angles of measurements, the corrections were less than 10%. The simulation corrections were verified through comparison to previously measured neutron angular distributions on the thick target plateau of the $E_\alpha = 1.05$ MeV resonance [33] and by measurements of the ^{7}Li$(p,n)^{7}$Be reaction [34, 35] from $E_p = 2.5$ to 4 MeV using the same setup. The significant sources of uncertainty are summarized in Table I. These dominate over the statistical uncertainties, which were only significant for the few lowest energy measurements. The present data set is shown in Fig. 1, and represents by far the most comprehensive experimental study of the differential cross section of the ^{13}C$(\alpha,n_0)^{16}$O reaction.

TABLE I. Summary of systematic uncertainty estimates.

Systematic Uncertainty Contribution	%
Charge Collection	3
Target Thickness	5
Intrinsic Efficiency	5
MCNP/Geometric Efficiency	10
Total	13

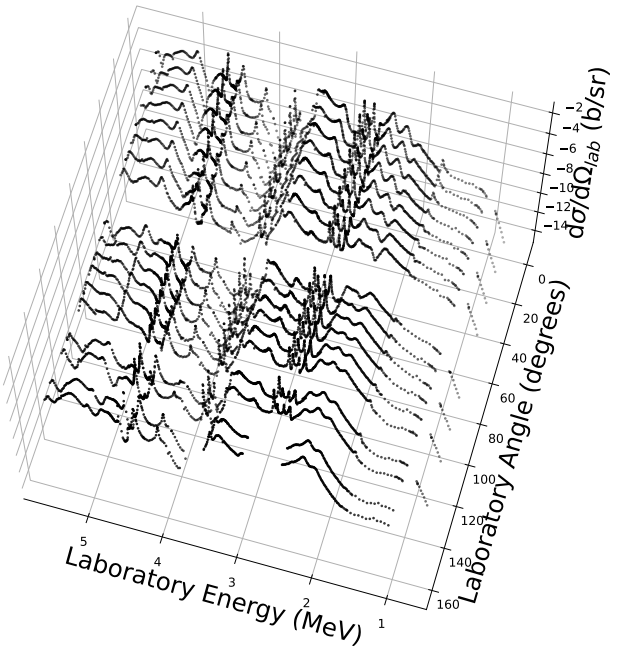

FIG. 1. The comprehensive differential cross section measurement of the ^{13}C$(\alpha,n_0)^{16}$O reaction of the present work.

The main reaction framework used for interpreting ^{13}C+α and ^{16}O+n data over the resolved resonance region has been phenomenological R-matrix theory [36, 37]. The most comprehensive analysis has been developed by the group at Los Alamos National Laboratory using the Energy Dependent Analysis (`EDA`) code [38]. The EDA

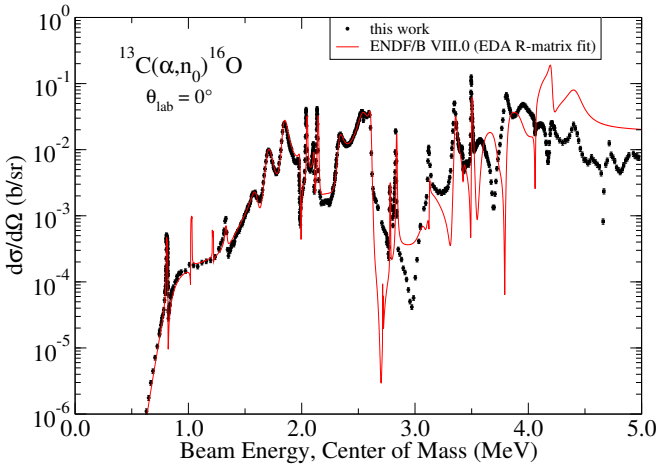

FIG. 2. Comparison of the present measurements with the R-matrix cross section at 0°, calculated from the parameters of the EDA fit used in the ENDF/B VIII.0 evaluation. The R-matrix cross section has been convoluted with the experimental resolution, which is quite significant over the narrow resonance ($\Gamma \approx 1.4$ keV) at $E_{\rm c.m.} \approx 0.80$ MeV.

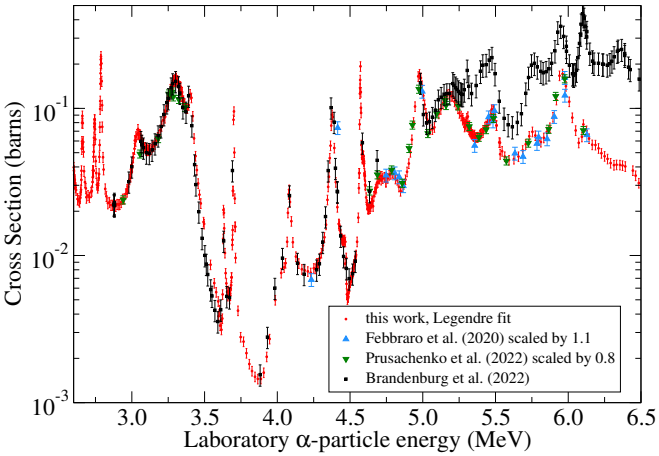

FIG. 3. Comparison of the present ^{13}C$(\alpha, n_0)^{16}$O data and that of Refs. [11, 46] to the total cross section data of Brandenburg *et al.* [47]. The data above $E_\alpha \approx 5$ MeV indicate strong contributions from excited state transitions.

R-matrix analysis has been used for the ENDF/B evaluations of ^{16}O+n reactions [13, 14] and it includes a large subset of all relevant experiment data available for these reactions. The R-matrix parameters from that work were transformed into the Brune parameterization [39] and used as initial fit parameters for the AZURE2 [40, 41] R-matrix analysis described here. These parameter conversions have been tested previously in Thompson *et al.* [42] for the ^{7}Be system.

Up to ≈2.6 MeV, the EDA R-matrix parameters give a good reproduction of the present measurements, but at higher energies the agreement worsens considerably. This is a direct result of the very limited availability of differential cross section data over this higher energy range. While at lower energies the EDA fit is constrained by the data of Walton *et al.* [33], at higher energies the only data are the far less comprehensive data of Refs. [43–45] and the very recent measurement of Prusachenko *et al.* [46], which has not been incorporated into the fit yet. This is demonstrated in the comparison of the 0° cross section shown in Fig. 2.

In Febbraro *et al.* [11] it was confirmed that above ≈5 MeV the transitions to the excited states in ^{16}O quickly become the dominant contributors to the reaction cross section. The present data now provide a much more complete mapping of the high energy ^{13}C$(\alpha, n_0)^{16}$O cross section. To be compared with the recent reaction cross section data of Brandenburg *et al.* [47], which is considerably more accurate than the data of Harissopulos *et al.* [18], the angular distributions of the present data were fit with a Legendre polynomial expansion to obtain an angle integrated ^{13}C$(\alpha, n_0)^{16}$O cross section. Over the region where only the ground state transition is energetically possible, the present data are in excellent agreement with those of Brandenburg *et al.* [47] and with those of Febbraro *et al.* [11], when they are scaled by a factor of 1.1, which is within their 15% systematic uncertainty. The present data are somewhat lower in absolute cross section than those of Prusachenko *et al.* [46], but agree in their energy dependence when that data is scaled by ≈0.8, which is, however, significantly larger than their quoted systematic uncertainty of 6.8%.

Recently, measurements of the ^{13}C$(\alpha, n)^{16}$O reaction have been extended to lower energies [3, 4], now directly overlapping a portion of the Gamow window for helium burning temperatures. Even with these lower energy measurements, an R-matrix extrapolation of the low energy cross section is still needed to extrapolate over the entire range of astrophysical interest. In addition, a comprehensive R-matrix analysis is a critical component in determining the best estimate of the S-factor, as it provides a framework for combining the several direct measurements, as well as asymptotic normalization coefficients (ANC) from α-transfer measurements, into a comprehensive evaluation. This is particularly important as there have also been several recent determinations of the near threshold state ANC [48–51] as well as investigations using the Trojan Horse Method [52].

To demonstrate the dramatic improvement that the present data set has on the low energy extrapolation of the S-factor, the uncertainty range of ≈30% based on data prior to 2020, as estimated in deBoer *et al.* [53], is shown in Fig. 4. As detailed in that work, this uncertainty stems from the large systematic difference in the different absolute cross section scales of Bair and Haas [15] and Harissopulos *et al.* [18] and the discrepancies between direct experimental data transfer measurements.

In 2021 and 2022, new very low energy experimental measurements were reported from the LUNA [3] and JUNA [4] underground facilities, respectively. While the data of [3] does not particularly favor one absolute cross

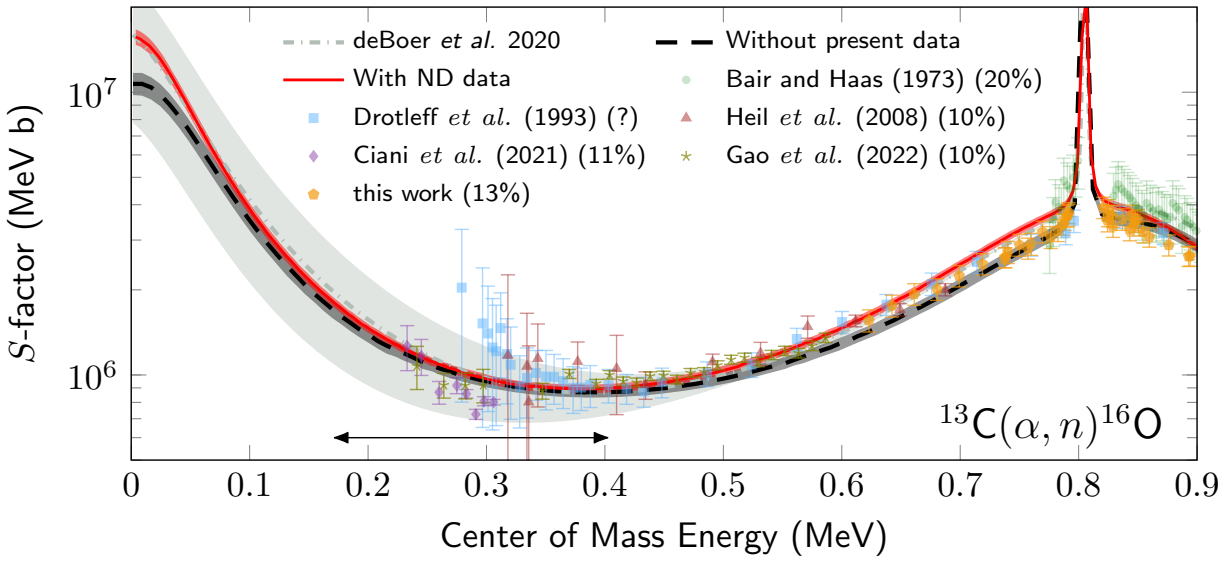

FIG. 4. S-factor plot for the $^{13}C(\alpha,n)^{16}O$ reaction at low energies. The shaded grey region indicates the large systematic uncertainty previously present [53]. The black and and red regions represent the 16 and 84% confidence limits obtained from the BRICK analysis. The percentages following each data set is the systematic uncertainty from that work. The arrow indicates the Gamow energy range for 0.2 GK.

section scale over another because it is limited to a small energy range at very low energies, the new experimental data of the present work and that of Gao *et al.* [4] strongly favor the larger absolute cross section scale consistent with Bair and Haas [15]. We thus assert that this source of systematic uncertainty has been greatly reduced in strong favor of the larger cross section solution.

As a first step for comparison, an R-matrix fit was performed that utilized the consistent $^{13}C(\alpha,n)^{16}O$ angle integrated cross section data of Refs. [3, 4, 15–17] up to $E_{c.m.} = 2.6$ MeV as well as the $^{16}O(n,\texttt{total})$ data of Refs. [54, 55] at overlapping excitation energy. A Bayesian uncertainty analysis was then performed using the code BRICK [56]. In addition to providing more detailed information about the parameter and cross section uncertainties through the calculated posterior probability distributions, this methodology provided a natural way for the sub-Coulomb ANC and its uncertainty for the near threshold state from Ref. [51] to be included directly in the analysis as a prior. The resulting best fit and uncertainty band is indicated in Fig. 4, which indicates a ≈10% uncertainty over the Gamow energy range. This fit and uncertainty analysis is similar to that performed in Ciani *et al.* [3], except without the systematic uncertainty of the absolute scale of the cross section.

The new differential cross section data were then added to the fit described above, resulting in a further reduction in the cross section uncertainty of a factor of two, to ≈5% over the Gamow energy range. The two fits are largely consistent with one another, indicating the consistency of the new data sets with previous ones, but the reduced uncertainty demonstrates the significantly greater constraint that the differential cross section data place on the R-matrix model. The added constraint from the differential cross section data is especially significant here given the presence of broad overlapping resonances of different spin-parity that produce complex and unique interference patterns.

The $^{13}C(\alpha,n)^{16}O$ reaction is one of the main sources of neutrons for s-process nucleosynthesis, it is a significant background in many large-volume, low-event-rate, neutrino and dark matter detectors, and its inverse $^{16}O(n,\alpha)^{13}C$ reaction is needed to model α-particle production in a variety of high neutron flux applications. The recent realization of additional sources of uncertainty in past $^{13}C(\alpha,n)^{16}O$ measurements using "4π" moderator type detectors has prompted new measurements of partial cross sections and their angular distributions using new experimental techniques. In this work, we report new high angular and energy resolution measurements of the $^{13}C(\alpha,n_0)^{16}O$ cross section, using the state-of-the-art ODeSA array, that encompasses the energy range from $E_\alpha = 0.8$ to 6.5 MeV, covering critical energy ranges for all of the above applications. The measurements have been made with unprecedented energy coverage in ≈10 keV energy steps resulting in over 700 distinct angular distributions. To compare these new data with past measurements and to demonstrate the effect of these new differential cross section measurements on the low energy cross section and extrapolated S-factor, several R-matrix fits were performed. Finally, by applying state-of-the-art Bayesian analysis to the R-matrix fits, using the newly

developed BRICK routine, it has been shown that the present measurements, when combined with the new low energy LUNA and JUNA measurements, further reduce the uncertainty in the low energy $^{13}C(\alpha,n)^{16}O$ extrapolated S-factor by a factor of two, reaching an uncertainty of $\approx$5% over the Gamow energy range.

ACKNOWLEDGMENTS

This research utilized resources from the Notre Dame Center for Research Computing. Researchers at the University of Notre Dame were funded by the National Science Foundation through Grant No. PHY-2011890 (University of Notre Dame Nuclear Science Laboratory) and Grant No. PHY-1430152 (the Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements). This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award Number DE-AC05-00OR22725.

[1] O. Straniero, R. Gallino, and S. Cristallo, *s* process in low-mass asymptotic giant branch stars, Nuclear Physics A **777**, 311 (2006), special Isseu on Nuclear Astrophysics.

[2] S. Bisterzo, C. Travaglio, M. Wiescher, F. Käppeler, and R. Gallino, Galactic chemical evolution: The impact of the 13c-pocket structure on the s-process distribution, The Astrophysical Journal **835**, 97 (2017).

[3] G. F. Ciani, L. Csedreki, D. Rapagnani, M. Aliotta, J. Balibrea-Correa, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, F. Cavanna, T. Chillery, P. Colombetti, P. Corvisiero, S. Cristallo, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, F. Ferraro, E. Fiore, A. Formicola, Z. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino, G. Gyürky, G. Imbriani, M. Junker, M. Lugaro, P. Marigo, E. Masha, R. Menegazzo, V. Mossa, F. R. Pantaleo, V. Paticchio, R. Perrino, D. Piatti, P. Prati, L. Schiavulli, K. Stöckel, O. Straniero, T. Szücs, M. P. Takács, F. Terrasi, D. Vescovi, and S. Zavatarelli (LUNA Collaboration), Direct Measurement of the $^{13}C(\alpha,n)^{16}O$ Cross Section into the *s*-Process Gamow Peak, Phys. Rev. Lett. **127**, 152701 (2021).

[4] B. Gao, T. Y. Jiao, Y. T. Li, H. Chen, W. P. Lin, Z. An, L. H. Ru, Z. C. Zhang, X. D. Tang, X. Y. Wang, N. T. Zhang, X. Fang, D. H. Xie, Y. H. Fan, L. Ma, X. Zhang, F. Bai, P. Wang, Y. X. Fan, G. Liu, H. X. Huang, Q. Wu, Y. B. Zhu, J. L. Chai, J. Q. Li, L. T. Sun, S. Wang, J. W. Cai, Y. Z. Li, J. Su, H. Zhang, Z. H. Li, Y. J. Li, E. T. Li, C. Chen, Y. P. Shen, G. Lian, B. Guo, X. Y. Li, L. Y. Zhang, J. J. He, Y. D. Sheng, Y. J. Chen, L. H. Wang, L. Zhang, F. Q. Cao, W. Nan, W. K. Nan, G. X. Li, N. Song, B. Q. Cui, L. H. Chen, R. G. Ma, Z. C. Zhang, S. Q. Yan, J. H. Liao, Y. B. Wang, S. Zeng, D. Nan, Q. W. Fan, N. C. Qi, W. L. Sun, X. Y. Guo, P. Zhang, Y. H. Chen, Y. Zhou, J. F. Zhou, J. R. He, C. S. Shang, M. C. Li, S. Kubono, W. P. Liu, R. J. deBoer, M. Wiescher, and M. Pignatari (JUNA Collaboration), Deep underground laboratory measurement of $^{13}C(\alpha,n)^{16}O$ in the gamow windows of the *s* and *i* processes, Phys. Rev. Lett. **129**, 132701 (2022).

[5] D. Carollo, K. Freeman, T. C. Beers, V. M. Placco, J. Tumlinson, and S. L. Martell, Carbon-Enhanced Metal-Poor Stars: CEMP-s and CEMP-no Subclasses in the Halo System of the Milky Way, The Astrophysical Journal **788**, 180 (2014).

[6] O. Clarkson, F. Herwig, and M. Pignatari, Pop III i-process nucleosynthesis and the elemental abundances of SMSS J0313âˆ'6708 and the most iron-poor stars, Monthly Notices of the Royal Astronomical Society: Letters **474**, L37 (2017), https://academic.oup.com/mnrasl/article-pdf/474/1/L37/24841490/slx190.pdf.

[7] O. Clarkson, F. Herwig, and M. Pignatari, Erratum: Pop III i-process nucleosynthesis and the elemental abundances of SMSS J0313-6708 the most iron-poor stars, Monthly Notices of the Royal Astronomical Society **488**, 222 (2019), https://academic.oup.com/mnras/article-pdf/488/1/222/31090328/stz1676.pdf.

[8] Choplin, A., Siess, L., and Goriely, S., The intermediate neutron capture process - i. development of the i-process in low-metallicity low-mass agb stars, A&A **648**, A119 (2021).

[9] A. Gando, Y. Gando, K. Ichimura, H. Ikeda, K. Inoue, Y. Kibe, Y. Kishimoto, M. Koga, Y. Minekawa, T. Mitsui, T. Morikawa, N. Nagai, K. Nakajima, K. Nakamura, K. Narita, I. Shimizu, Y. Shimizu, J. Shirai, F. Suekane, A. Suzuki, H. Takahashi, N. Takahashi, Y. Takemoto, K. Tamae, H. Watanabe, B. D. Xu, H. Yabumoto, H. Yoshida, S. Yoshida, S. Enomoto, A. Kozlov, H. Murayama, C. Grant, G. Keefer, A. Piepke, T. I. Banks, T. Bloxham, J. A. Detwiler, S. J. Freedman, B. K. Fujikawa, K. Han, R. Kadel, T. O'Donnell, H. M. Steiner, D. A. Dwyer, R. D. McKeown, C. Zhang, B. E. Berger, C. E. Lane, J. Maricic, T. Miletic, M. Batygov, J. G. Learned, S. Matsuno, M. Sakai, G. A. Horton-Smith, K. E. Downum, G. Gratta, Y. Efremenko, O. Perevozchikov, H. J. Karwowski, D. M. Markoff, W. Tornow, K. M. Heeger, and M. P. Decowski (The KamLAND Collaboration), Constraints on θ_{13} from a three-flavor oscillation analysis of reactor antineutrinos at kamland, Phys. Rev. D **83**, 052002 (2011).

[10] K. Ichimura and Y. Minekawa, Background study for the kamland reactor neutrino experiment, Journal of Physics: Conference Series **120**, 052034 (2008).

[11] M. Febbraro, R. J. deBoer, S. D. Pain, R. Toomey, F. D. Becchetti, A. Boeltzig, Y. Chen, K. A. Chipps, M. Couder, K. L. Jones, E. Lamere, Q. Liu, S. Lyons, K. T. Macon, L. Morales, W. A. Peters, D. Robertson, B. C. Rasco, K. Smith, C. Seymour, G. Seymour, M. S. Smith, E. Stech, B. V. Kolk, and M. Wiescher, New $^{13}C(\alpha,n)^{16}O$ cross section with implications for neutrino mixing and geoneutrino measurements, Phys. Rev. Lett.

125, 062501 (2020).
[12] R. J. deBoer, A. Gula, M. Febbraro, K. Brandenburg, C. R. Brune, J. Görres, G. Gyürky, R. Kelmar, K. Manukyan, Z. Meisel, D. Odell, M. T. Pigni, Shahina, E. Stech, W. Tan, and M. Wiescher, First near-threshold measurements of the $^{13}C(\alpha, n_1)^{16}O$ reaction for low-background-environment characterization, Phys. Rev. C **106**, 055808 (2022).
[13] M. Chadwick, R. Capote, A. Trkov, M. Herman, D. Brown, G. Hale, A. Kahler, P. Talou, A. Plompen, P. Schillebeeckx, M. Pigni, L. Leal, Y. Danon, A. Carlson, P. Romain, B. Morillon, E. Bauge, F.-J. Hambsch, S. Kopecky, G. Giorginis, T. Kawano, J. Lestone, D. Neudecker, M. Rising, M. Paris, G. Nobre, R. Arcilla, O. Cabellos, I. Hill, E. Dupont, A. Koning, D. Cano-Ott, E. Mendoza, J. Balibrea, C. Paradela, I. Durán, J. Qian, Z. Ge, T. Liu, L. Hanlin, X. Ruan, W. Haicheng, M. Sin, G. Noguere, D. Bernard, R. Jacqmin, O. Bouland, C. De Saint Jean, V. Pronyaev, A. Ignatyuk, K. Yokoyama, M. Ishikawa, T. Fukahori, N. Iwamoto, O. Iwamoto, S. Kunieda, C. Lubitz, M. Salvatores, G. Palmiotti, I. Kodeli, B. Kiedrowski, D. Roubtsov, I. Thompson, S. Quaglioni, H. Kim, Y. Lee, U. Fischer, S. Simakov, M. Dunn, K. Guber, J. Márquez Damián, F. Cantargi, I. Sirakov, N. Otuka, A. Daskalakis, B. McDermott, and S. van der Marck, Cielo collaboration summary results: International evaluations of neutron reactions on uranium, plutonium, iron, oxygen and hydrogen, Nuclear Data Sheets **148**, 189 (2018), special Issue on Nuclear Reaction Data.
[14] D. Brown, M. Chadwick, R. Capote, A. Kahler, A. Trkov, M. Herman, A. Sonzogni, Y. Danon, A. Carlson, M. Dunn, D. Smith, G. Hale, G. Arbanas, R. Arcilla, C. Bates, B. Beck, B. Becker, F. Brown, R. Casperson, J. Conlin, D. Cullen, M.-A. Descalle, R. Firestone, T. Gaines, K. Guber, A. Hawari, J. Holmes, T. Johnson, T. Kawano, B. Kiedrowski, A. Koning, S. Kopecky, L. Leal, J. Lestone, C. Lubitz, J. Márquez Damián, C. Mattoon, E. McCutchan, S. Mughabghab, P. Navratil, D. Neudecker, G. Nobre, G. Noguere, M. Paris, M. Pigni, A. Plompen, B. Pritychenko, V. Pronyaev, D. Roubtsov, D. Rochman, P. Romano, P. Schillebeeckx, S. Simakov, M. Sin, I. Sirakov, B. Sleaford, V. Sobes, E. Soukhovitskii, I. Stetcu, P. Talou, I. Thompson, S. van der Marck, L. Welser-Sherrill, D. Wiarda, M. White, J. Wormald, R. Wright, M. Zerkle, G. Žerovnik, and Y. Zhu, ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data, Nuclear Data Sheets **148**, 1 (2018), special Issue on Nuclear Reaction Data.
[15] J. K. Bair and F. X. Haas, Total neutron yield from the reactions $^{13}C(\alpha, n)^{16}O$ and $^{17,18}O(\alpha, n)^{20,21}Ne$, Phys. Rev. C **7**, 1356 (1973).
[16] H. W. Drotleff, A. Denker, H. Knee, M. Soine, G. Wolf, J. W. Hammer, U. Greife, C. Rolfs, and H. P. Trautvetter, Reaction rates of the s-process neutron sources $^{22}N(\alpha, n)^{25}Mg$ and $^{13}C(\alpha, n)^{16}O$, Astrophys. J. **414**, 735 (1993).
[17] M. Heil, R. Detwiler, R. E. Azuma, A. Couture, J. Daly, J. Görres, F. Käppeler, R. Reifarth, P. Tischhauser, C. Ugalde, and M. Wiescher, The $^{13}C(\alpha, n)$ reaction and its role as a neutron source for the *s* process, Phys. Rev. C **78**, 025803 (2008).
[18] S. Harissopulos, H. W. Becker, J. W. Hammer, A. Lagoyannis, C. Rolfs, and F. Strieder, Cross section of the $^{13}C(\alpha, n)^{16}O$ reaction: A background for the measurement of geo-neutrinos, Phys. Rev. C **72**, 062801 (2005).
[19] W. A. Peters, Comment on "Cross section of the $^{13}C(\alpha, n)^{16}O$ reaction: A background for the measurement of geo-neutrinos", Phys. Rev. C **96**, 029801 (2017).
[20] P. Mohr, Revised cross section of the $^{13}C(\alpha, n)^{16}O$ reaction between 5 and 8 MeV, Phys. Rev. C **97**, 064613 (2018).
[21] M. Chadwick, M. Herman, P. Obložinský, M. Dunn, Y. Danon, A. Kahler, D. Smith, B. Pritychenko, G. Arbanas, R. Arcilla, R. Brewer, D. Brown, R. Capote, A. Carlson, Y. Cho, H. Derrien, K. Guber, G. Hale, S. Hoblit, S. Holloway, T. Johnson, T. Kawano, B. Kiedrowski, H. Kim, S. Kunieda, N. Larson, L. Leal, J. Lestone, R. Little, E. McCutchan, R. MacFarlane, M. MacInnes, C. Mattoon, R. McKnight, S. Mughabghab, G. Nobre, G. Palmiotti, A. Palumbo, M. Pigni, V. Pronyaev, R. Sayer, A. Sonzogni, N. Summers, P. Talou, I. Thompson, A. Trkov, R. Vogt, S. van der Marck, A. Wallner, M. White, D. Wiarda, and P. Young, ENDF/B-VII.1 Nuclear Data for Science and Technology: Cross Sections, Covariances, Fission Product Yields and Decay Data, Nuclear Data Sheets **112**, 2887 (2011), special Issue on ENDF/B-VII.1 Library.
[22] R. H. Spear, J. D. Larson, and J. D. Pearson, Excitation function for the reaction $C^{13}(\alpha, n\gamma)O^{16}O$, Nuclear Physics **41**, 353 (1963).
[23] A. Aprahamian, P. Collon, and M. Wiescher, The nuclear science laboratory at the university of notre dame, Nuclear Physics News **24**, 5 (2014), https://doi.org/10.1080/10619127.2014.882732.
[24] G. F. Ciani, L. Csedreki, J. Balibrea-Correa, A. Best, M. Aliotta, F. Barile, D. Bemmerer, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, F. Cavanna, T. Chillery, P. Colombetti, P. Corvisiero, T. Davinson, R. Depalo, A. Di Leva, L. Di Paolo, Z. Elekes, F. Ferraro, E. M. Fiore, A. Formicola, Z. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino, G. Gyürky, G. Imbriani, M. Junker, I. Kochanek, M. Lugaro, P. Marigo, E. Masha, R. Menegazzo, V. Mossa, F. R. Pantaleo, V. Paticchio, R. Perrino, D. Piatti, P. Prati, L. Schiavulli, K. Stöckel, O. Straniero, T. Szücs, M. P. TakÃ¡cs, F. Terrasi, D. Trezzi, and S. Zavatarelli, A new approach to monitor ^{13}C-targets degradation in situ for $^{13}C(\alpha, n)^{16}O$ cross-section measurements at LUNA, The European Physical Journal A **56**, 10.1140/epja/s10050-020-00077-0 (2020).
[25] M. Febbraro, R. Toomey, S. Pain, K. Chipps, B. Becker, R. Newby, Z. Meisel, T. Massey, C. Brune, Q. Liu, R. deBoer, K. Macon, A. Boeltzig, J. O'Neill, M. Smith, M. Wiescher, D. Soltesz, I. Sultana, K. Brandenburg, S. Subedi, S. Paneru, T. Danley, and Y. Alberty-Jones, The ORNL Deuterated Spectroscopic Array — ODeSA, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **946**, 162668 (2019).
[26] Q. Liu, M. Febbraro, R. J. deBoer, A. Boeltzig, Y. Chen, C. Cerjan, M. Couder, B. Frentz, J. Görres, E. A. Henry, E. Lamere, K. T. Macon, K. V. Manukyan, L. Morales, P. D. O'Malley, S. D. Pain, W. A. Peters, D. Schneider, C. Seymour, G. Seymour, E. Temanson, R. Toomey, B. Vande Kolk, J. Weaver, and M. Wi-

escher, Measurement of the ^{10}B$(\alpha, n_0)^{13}$N cross section for $2.2 < E_\alpha < 4.9$ MeV and its application as a diagnostic at the National Ignition Facility, Phys. Rev. C **100**, 034601 (2019).

[27] Q. Liu, M. Febbraro, R. J. deBoer, S. Aguilar, A. Boeltzig, Y. Chen, M. Couder, J. Görres, E. Lamere, S. Lyons, K. T. Macon, K. Manukyan, L. Morales, S. Pain, W. A. Peters, C. Seymour, G. Seymour, R. Toomey, B. V. Kolk, J. Weaver, and M. Wiescher, Low-energy cross-section measurement of the ^{10}B$(\alpha, n)^{13}$N reaction and its impact on neutron production in first-generation stars, Phys. Rev. C **101**, 025808 (2020).

[28] T. N. Massey, D. K. Jacobs, S. I. Al-Quraishi, S. M. Grimes, C. E. Brient, W. B. Howard, and J. C. Yanch, Study of the Be(p, n) and Be(d, n) Source Reactions, Journal of Nuclear Science and Technology **39**, 677 (2002), https://doi.org/10.1080/00223131.2002.10875190.

[29] J. W. Meadows, The ^{9}Be(d, n) thick-target neutron spectra for deuteron energies between 2.6 and 7.0 MeV, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **324**, 239 (1993).

[30] M. Febbraro, C. Lawrence, H. Zhu, B. Pierson, R. Torres-Isea, F. Becchetti, J. Kolata, and J. Riggins, Deuterated scintillators and their application to neutron spectroscopy, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **784**, 184 (2015), symposium on Radiation Measurements and Applications 2014 (SORMA XV).

[31] M. Febbraro, B. Becker, R. deBoer, K. Brandenburg, C. Brune, K. Chipps, T. Danley, A. D. Fulvio, Y. Jones-Alberty, K. Macon, Z. Meisel, T. Massey, R. Newby, S. Pain, S. Paneru, S. Shahina, M. Smith, D. Soltesz, S. Subedi, I. Sultana, and R. Toomey, Performance of neutron spectrum unfolding using deuterated liquid scintillator, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **989**, 164824 (2021).

[32] T. Goorley, M. James, T. Booth, F. Brown, J. Bull, L. Cox, J. Durkee, J. Elson, M. Fensin, R. Forster, J. Hendricks, H. Hughes, R. Johns, B. Kiedrowski, R. Martz, S. Mashnik, G. McKinney, D. Pelowitz, R. Prael, J. Sweezy, L. Waters, T. Wilcox, and T. Zukaitis, Features of MCNP6, Annals of Nuclear Energy **87**, 772 (2016).

[33] R. B. Walton, J. D. Clement, and F. Boreli, Interaction of Neutrons with Oxygen and a Study of the $C^{13}(\alpha, n)O^{16}$ Reaction, Phys. Rev. **107**, 1065 (1957).

[34] S. Elbakr, I. Van Heerden, W. McDonald, and G. Neilson, Measurements of neutron angular distributions from the ^{7}Li$(p, n)^7$Be reaction, Nuclear Instruments and Methods **105**, 519 (1972).

[35] C. A. Burke, M. T. Lunnon, and H. W. Lefevre, ^{7}Li$(p, n_0)^7$Be angular distributions to $E_p = 3.8$ MeV, Phys. Rev. C **10**, 1299 (1974).

[36] A. M. Lane and R. G. Thomas, R-matrix theory of nuclear reactions, Rev. Mod. Phys. **30**, 257 (1958).

[37] P. Descouvemont and D. Baye, The R-matrix theory, Rep. Prog. Phys. **73**, 036301 (2010).

[38] D. Dodder, G. Hale, , and K. Witte, The Energy Dependent Analysis Code, Los Alamos National Laboratory, (unpublished, 1972).

[39] C. R. Brune, Alternative parametrization of R -matrix theory, Phys. Rev. C **66**, 044611 (2002).

[40] R. E. Azuma, E. Uberseder, E. C. Simpson, C. R. Brune, H. Costantini, R. J. de Boer, J. Görres, M. Heil, P. J. LeBlanc, C. Ugalde, and M. Wiescher, AZURE: An R-matrix code for nuclear astrophysics, Phys. Rev. C **81**, 045805 (2010).

[41] E. Uberseder and R. J. deBoer, *AZURE2 User Manual* (2015).

[42] I. Thompson, R. deBoer, P. Dimitriou, S. Kunieda, M. Pigni, G. Arbanas, H. Leeb, T. Srdinko, G. Hale, P. Tamagno, and P. Archier, Verification of R-matrix calculations for charged-particle reactions in the resolved resonance region for the ^{7}Be system, European Physical Journal A **55**, 92 (2019).

[43] T. W. Bonner, A. A. Kraus, J. B. Marion, and J. P. Schiffer, Neutrons and Gamma Rays from the Alpha-Particle Bombardment of Be^9, B^{10}, B^{11}, C^{13}, and O^{18}, Phys. Rev. **102**, 1348 (1956).

[44] A. Robb, W. Schier, and E. Sheldon, Spin and parity assignments for ^{17}O levels from the ^{13}C$(\alpha, n)^{16O}$ g.s. reaction, Nuclear Physics A **147**, 423 (1970).

[45] G. W. Kerr, J. M. Morris, and J. R. Risser, Energy levels of ^{17}O from ^{13}C$(\alpha, \alpha_0)^{13}$C and ^{13}C$(\alpha, n)^{16}$O, Nuclear Physics A **110**, 637 (1968).

[46] P. S. Prusachenko, T. L. Bobrovsky, I. P. Bondarenko, M. V. Bokhovko, A. F. Gurbich, and V. V. Ketlerov, Measurement of the cross section for the ^{13}C$(\alpha, n)^{16}$O reaction and determination of the cross section for the ^{16}O$(n, \alpha)^{13}$C reaction, Phys. Rev. C **105**, 024612 (2022).

[47] K. Brandenburg, G. Hamad, Z. Meisel, C. R. Brune, D. E. Carter, R. deBoer, J. Derkin, C. Feathers, D. Ingram, Y. Jones-Alberty, B. Kenady, T. N. Massey, M. Saxena, D. Soltesza, S. K. Subedi, A. V. Voinov, J. Warren, , and M. Wiescher, Measurements of the ^{13}C$(\alpha, n)^{16}$O Cross Section up to $E_\alpha = 8$ MeV, unpublished.

[48] S. Y. Mezhevych, A. T. Rudchik, A. A. Rudchik, O. A. Ponkratenko, N. Keeley, K. W. Kemper, M. Mazzocco, K. Rusek, and S. B. Sakuta, Cluster structure of ^{17}O, Phys. Rev. C **95**, 034607 (2017).

[49] M. G. Pellegriti, F. Hammache, P. Roussel, L. Audouin, D. Beaumel, P. Descouvemont, S. Fortier, L. Gaudefroy, J. Kiener, A. Lefebvre-Schuhl, M. Stanoiu, V. Tatischeff, and M. Vilmay, Indirect study of the ^{13}C$(\alpha, n)^{16}$O reaction via the ^{13}C$(^7$Li$,t)^{17}$O transfer reaction, Phys. Rev. C **77**, 042801 (2008).

[50] B. Guo, Z. H. Li, M. Lugaro, J. Buntain, D. Y. Pang, Y. J. Li, J. Su, S. Q. Yan, X. X. Bai, Y. S. Chen, Q. W. Fan, S. J. Jin, A. I. Karakas, E. T. Li, Z. C. Li, G. Lian, J. C. Liu, X. Liu, J. R. Shi, N. C. Shu, B. X. Wang, Y. B. Wang, S. Zeng, and W. P. Liu, New determination of the ^{13}c$(\alpha, n)^{17}$o reaction rate and its influence on the s-process nucleosynthesis in the agb stars, The Astrophysical Journal **756**, 193 (2012).

[51] M. L. Avila, G. V. Rogachev, E. Koshchiy, L. T. Baby, J. Belarge, K. W. Kemper, A. N. Kuchera, and D. Santiago-Gonzalez, New measurement of the α asymptotic normalization coefficient of the $1/2^+$ state in ^{17}O at 6.356 MeV that dominates the ^{13}C$(\alpha, n)^{16}$O reaction rate at temperatures relevant for the s process, Phys. Rev. C **91**, 048801 (2015).

[52] M. La Cognata, C. Spitaleri, O. Trippella, G. G. Kiss,

G. V. Rogachev, A. M. Mukhamedzhanov, M. Avila, G. L. Guardo, E. Koshchiy, A. Kuchera, L. Lamia, S. M. R. Puglia, S. Romano, D. Santiago, and R. Spartà, On the measurement of the ^{13}C$(\alpha,n)^{16}$O S-factor at negative energies and its influence on the s-process, The Astrophysical Journal **777**, 143 (2013).

[53] R. J. deBoer, C. R. Brune, M. Febrarro, J. Görres, I. J. Thompson, and M. Wiescher, Sensitivity of the ^{13}C$(\alpha,n)^{16}$O S factor to the uncertainty in the level parameters of the near-threshold state, Phys. Rev. C **101**, 045802 (2020).

[54] J. L. Fowler, C. H. Johnson, and R. M. Feezel, Level structure of ^{17}O from neutron total cross sections, Phys. Rev. C **8**, 545 (1973).

[55] S. Cierjacks, F. Hinterberger, G. Schmalz, D. Erbe, P. Rossen, and B. Leugers, High precision time-of-flight measurements of neutron resonance energies in carbon and oxygen between 3 and 30 MeV, Nuclear Instruments and Methods **169**, 185 (1980).

[56] D. Odell, C. R. Brune, D. R. Phillips, R. J. deBoer, and S. N. Paneru, Performing Bayesian Analyses With `AZURE2` Using `BRICK`: An Application to the ^{7}Be System, Frontiers in Physics **10**, 888476 (2022).