



CHORUS

This is the accepted manuscript made available via CHORUS. The article has been published as:

New measurement of the α asymptotic normalization coefficient of the $1/2^{+}$ state in ^{17}O at 6.356 MeV that dominates the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction rate at temperatures relevant for the s process

M. L. Avila, G. V. Rogachev, E. Koshchiy, L. T. Baby, J. Belarge, K. W. Kemper, A. N. Kuchera, and D. Santiago-Gonzalez

Phys. Rev. C **91**, 048801 — Published 16 April 2015

DOI: [10.1103/PhysRevC.91.048801](https://doi.org/10.1103/PhysRevC.91.048801)

New α ANC measurement of the $1/2^+$ state in ^{17}O at 6.356 MeV, that dominates the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction rate at temperatures relevant for the s-process

M.L. Avila,^{1,*} G.V. Rogachev,^{2,†} E. Koshchiy,² L.T. Baby,¹ J.

Belarge,¹ K.W. Kemper,¹ A.N. Kuchera,^{1,‡} and D. Santiago-Gonzalez^{1,§}

¹*Department of Physics, Florida State University, Tallahassee, FL 32306, USA*

²*Department of Physics&Astronomy and Cyclotron Institute,
Texas A&M University, College Station, TX 77843, USA*

Abstract

Background: Accurate knowledge of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction cross section is important for the understanding of the s-process in AGB stars, since it is considered to be the main source of neutrons. The sub-threshold $1/2^+$ state at excitation energy of 6.356 MeV in ^{17}O has a strong influence on the reaction cross section at energies relevant for astrophysics. Several experiments have been performed to determine the contribution of this state to the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction rate. Nevertheless, significant discrepancies between different measurements remain.

Purpose: The aim of this work is to investigate these discrepancies.

Method: An 8 MeV ^{13}C beam (below the Coulomb barrier) was used to study the α -transfer reaction $^6\text{Li}(^{13}\text{C},d)^{17}\text{O}$.

Results: The squared Coulomb modified ANC of the $1/2^+$ state in ^{17}O measured in this work is $(\tilde{C}_{\alpha-^{13}\text{C}}^{^{17}\text{O}(1/2^+)})^2 = 3.6 \pm 0.7 \text{ fm}^{-1}$.

Conclusions: Discrepancy between the results of α -transfer experiments have been resolved. However, some discrepancy with the most recent measurement using the Trojan Horse method remains.

* mavila@anl.gov; Physics Division, Argonne National Laboratory, Argonne IL 60439, USA

† rogachev@tamu.edu

‡ National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA

§ Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA

I. INTRODUCTION

The slow neutron capture process or s-process, occurs in a relatively low neutron density environment in Asymptotic Giant Branch (AGB) stars. This process is essential for the nucleosynthesis of heavier elements. It is believed that the s-process is responsible for nearly half of the heavy elements observed in the Universe [1]. The main characteristic of this process, is that the neutron capture is slower than the β decay. At low temperature ($< 10^8$ K) for low mass stars the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction plays the major role and is considered to be the main source of neutrons for the s-process in such stars [2]. Thus, this reaction rate is a necessary ingredient for constraining the models of AGB stars. Direct measurements are only available for center of mass energies above 279 keV. Below this energy the cross section has to be extrapolated. Extrapolation to lower energies causes a large uncertainty due to the presence of a sub-threshold $1/2^+$ resonance in ^{17}O at excitation energy of 6.356 MeV (3 keV below the $^{13}\text{C}+\alpha$ threshold energy). This sub-threshold resonance enhances the cross section at low energies making an important contribution to the astrophysical S-factor.

The $1/2^+$ state at 6.356 MeV has been the subject of several investigations [3–9]. Kubono *et al.* [3] measured the spectroscopic factor of the $1/2^+$ state using the $^{13}\text{C}(^6\text{Li}, d)^{17}\text{O}$ reaction at 60 MeV of ^6Li . A very small α spectroscopic factor of $S_\alpha = 0.011$ was found in this study. This value suggested a very small contribution of this sub-threshold state to the cross section. However, using the same experimental data it was shown by Keeley *et al.* [4] that the data is consistent with S_α ranging from 0.15 to 0.41 depending on the DWBA parameters used. Later, Johnson *et al.* [5] studied the α -transfer reaction $^{13}\text{C}(^6\text{Li}, d)^{17}\text{O}$ at sub-Coulomb energies obtaining a squared Coulomb modified ANC value of $(\tilde{C}_{\alpha-^{13}\text{C}}^{^{17}\text{O}(1/2^+)})^2 = 0.89 \pm 0.23 \text{ fm}^{-1}$. This ANC corresponds to a contribution of this state to the astrophysical S-factor at zero energy of a factor of five larger than the one extracted in Ref. [3]. However it produced a relatively small enhancement at the Gamow window energies for the s-process (around 180 keV). Pellegriti *et al.* [6] used the $^{13}\text{C}(^7\text{Li}, t)^{17}\text{O}$ transfer reaction above Coulomb barrier energies (^7Li beam energies of 28 and 34 MeV) obtaining a squared Coulomb modified ANC of $(\tilde{C}_{\alpha-^{13}\text{C}}^{^{17}\text{O}(1/2^+)})^2 = 4.5 \pm 2.2 \text{ fm}^{-1}$, which is a factor of 5 larger than the one from Johnson *et al.* [5]. Heil *et al.* [7] performed a comprehensive R-Matrix analyses of all available data, including the direct measurements of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction cross section down to a c.m. energy of 320 keV and extrapolated the cross section to the astrophysically relevant energies

(below 200 keV). Their extrapolations agree with the S-factor curve found by Pellegriti *et al.* [6]. Guo *et al.* [8] evaluated a squared Coulomb modified ANC of $(\tilde{C}_{\alpha-^{13}\text{C}}^{^{17}\text{O}(1/2+)})^2 = 4.0 \pm 1.1 \text{ fm}^{-1}$ using the reaction $^{13}\text{C}(^{11}\text{B}, ^7\text{Li})^{17}\text{O}$ with ^{11}B beam energy of 50 MeV. This result is in good agreement with Pellegriti *et al.* [6]. More recently, the ANC of the $1/2^+$ state was determined by La Cognata *et al.* [10] using the Trojan Horse technique (^6Li beam energy of 7.82 MeV) extracting a squared Coulomb modified ANC value of $(\tilde{C}_{\alpha-^{13}\text{C}}^{^{17}\text{O}(1/2+)})^2 = 6.7 \pm 0.6 \text{ fm}^{-1}$ that was later revised to $(\tilde{C}_{\alpha-^{13}\text{C}}^{^{17}\text{O}(1/2+)})^2 = 7.7 \pm 0.3_{\text{stat}}^{+1.6}_{-1.5 \text{ norm}} \text{ fm}^{-1}$ in Ref. [9]. This value is higher than those reported in Refs. [6, 8], however it is within the large uncertainties of Ref. [6].

The values of the ANC measured at above barrier energies in Refs. [6, 8, 9] are at least 4 times larger than the value measured at the sub-Coulomb energy in Ref. [5]. The main goal of this work is to remeasure the ANC using the sub-Coulomb α -transfer reaction used by Johnson *et al.* [5] and resolve the discrepancies between the ANC measured at sub-Coulomb energies and the ANC measured at above Coulomb barrier energies. The application of the sub-Coulomb α -transfer ANC technique was pioneered in Ref. [11], where the α -transfer reactions $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}$ and $^{12}\text{C}(^7\text{Li}, t)^{16}\text{O}$ were used to study the sub-threshold 2^+ and 1^- states in ^{16}O at 6.92 and 7.12 MeV, respectively. More recently, the validity of the sub-Coulomb α -transfer approach was demonstrated in Ref. [12] by measuring the ANC of the 1^- state at 5.9 MeV in ^{20}Ne and comparing it to the well known width of this state. Also, the 0^+ and 3^- cascade transitions for one of the most astrophysically important reactions, $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$, were constrained using this approach [13].

II. EXPERIMENTAL SETUP AND ANALYSIS

The experiment was carried out at the John D. Fox Superconducting Accelerator Laboratory, at Florida State University. A ^{13}C beam at energy of 8 MeV was used. Inverse kinematics (heavy beam and light target) was chosen to achieve the lowest energies in the center of mass (c.m.) and still be able to detect the recoil deuterons. The ^{13}C beam was delivered by an FN Tandem Van de Graaff accelerator using a SNICS-II cesium-sputter ion source. Several different ^6Li targets of about $35 \mu\text{g}/\text{cm}^2$ thick were used. The ^6Li targets were prepared under vacuum and transported to the chamber in a vacuum container to prevent oxidation. For the identification of the reaction products two ΔE - E telescopes were

mounted on remotely controlled rotating rings placed to the right and left of the beam axis. Each of the ΔE - E telescopes were constructed with four pin diode 2×2 cm² silicon detectors and one position sensitive proportional counter wire, contained in a box filled with a P10 gas (10% methane and 90% Ar gas mixture). A Kapton foil of 7.5 μ m thickness was used as the entrance window separating the P10 gas inside the detector from the chamber vacuum. This setup allows the measurement and identification of deuterons down to an energy of 1.8 MeV when a pressure of 150 Torr for P10 is used and also to observe the ⁶Li ions scattered at forward angles in the laboratory reference frame when the pressure in the proportional counters is reduced to 50 Torr. The intensity of the incoming beam was measured using a Faraday cup placed at the end of the chamber.

The target thickness was measured using elastically scattered ⁶Li from the target (at forward angles in the laboratory reference frame) by a ¹³C beam at 8 MeV and a ¹⁶O beam at 10 MeV. Two different beams were used to evaluate the systematic uncertainty of the target thickness measurements which turned out to be 10%. Elastic scattering of ⁶Li was also used to monitor target integrity and effective thickness. The control measurements were performed every time a new target was used and after about three hours of use. It was found that after 3-5 hours of target usage the energy of the elastically scattered ⁶Li reduces slightly. This was attributed to some material buildup on the surface of the target (probably carbon or oxygen). Since the sub-Coulomb α -transfer cross section is very sensitive to the energy of the beam, the targets were changed every 3 to 5 hours and corresponding corrections were implemented. Details are given in Refs. [12, 14]. After the energy correction due to the energy loss in the buildup material in the target, an effective energy of interaction of 7.72 MeV was calculated by taking into account the energy dependence of the cross section. The effective energy of interaction is calculated by integrating the cross section over the full target thickness and obtaining the value of the energy in the target at which one-half of the yield is achieved, as is explained in Ref. [15]. Thus, the beam energy of 7.72 MeV is used for all the calculations presented in this work.

A two-dimensional E vs ΔE spectrum is shown in Fig. 1 for a laboratory angle of 20°. In this figure an intense proton region is observed at around 1.8 MeV. This proton background corresponds to ¹³C+ p elastic scattering due to hydrogen contained in the target. In Fig. 1 the deuterons that correspond to the $1/2^+$ state of interest are located at the left corner of the deuteron contour. This state can be well separated from the intense proton background

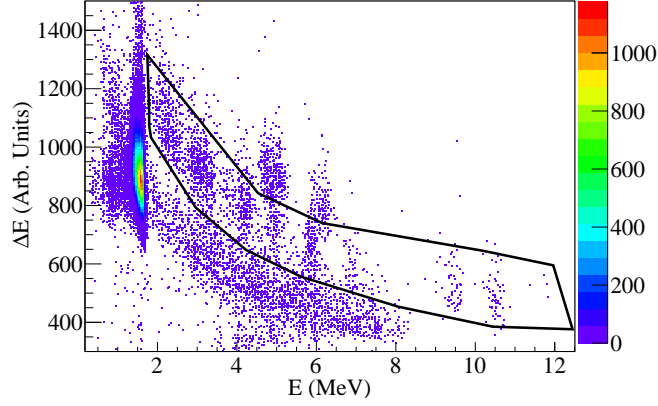


FIG. 1. ΔE vs E 2D scatter plot observed by a pin detector at 20° in the laboratory reference frame and used for particle identification. The typical deuterons cut is shown by solid line.

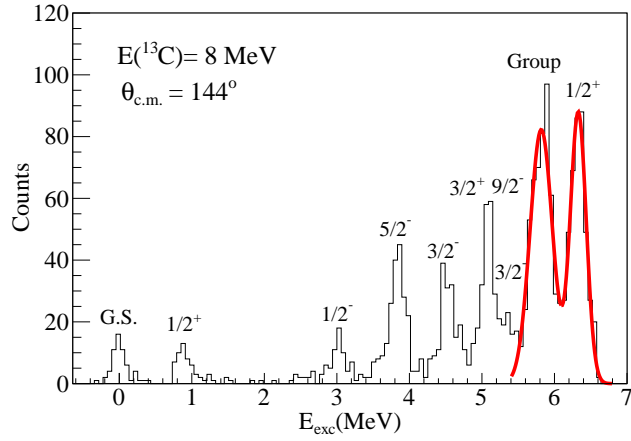


FIG. 2. Spectrum of deuterons from the ${}^6\text{Li}({}^{13}\text{C}, d){}^{17}\text{O}$ reaction at 8 MeV (7.72 MeV effective energy after energy loss corrections)

of ${}^{13}\text{C}$ beam at 144° in c.m.

from the elastically scattered protons. The reconstructed excitation energy of ${}^{17}\text{O}$ at the center of mass angle of 144° is shown in Fig. 2. In this figure all the labeled peaks that are produced correspond to well known states. The peak labeled as Group contains the four states $7/2^+$ (5.70 MeV), $5/2^-$ (5.73 MeV), $3/2^+$ (5.87 MeV) and $1/2^-$ (5.94 MeV) that could not be resolved. It can be seen in this figure that the $1/2^+$ state at 6.356 MeV is well separated from this neighboring group of states.

The angular distribution for population of the $1/2^+$ state at 6.356 MeV and the Distorted Wave Born Approximation (DWBA) fit are shown in Fig. 3. The DWBA calculations were

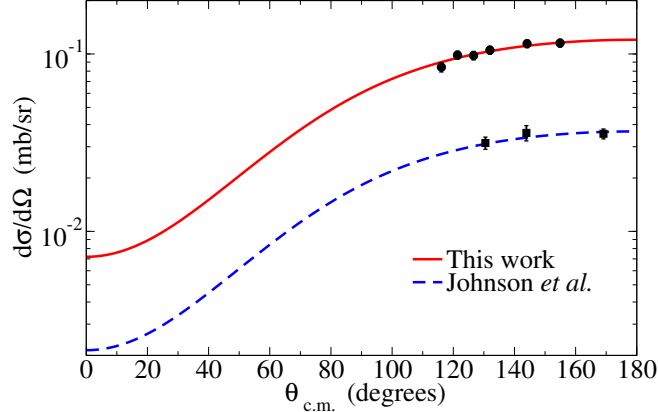


FIG. 3. Cross section and DWBA fit as a function of center of mass angle of the $1/2^+$ sub-threshold resonance state of excitation energy 6.356 MeV in ^{17}O measured in the present work (solid line) and in Ref. [5] (dashed line) using a ^{13}C beam energy of 7.72 MeV and 7.81 MeV respectively.

done using the FRESKO code (version FRES 2.9) [16] in the finite-range transfer approach with a full complex remnant term. The $d+^{17}\text{O}$ and $d+^{12}\text{C}$ optical parameters that were used are the same parameters used to fit the $^{13}\text{C}(^6\text{Li},d)^{17}\text{O}$ data in [5]. The radius of $R_v = 1.9$ fm and diffuseness of $a = 0.65$ fm were used for the $\alpha+d$ form-factor potential. These parameters are the same as in [17]. The potential depth was fitted to reproduce the binding energy of ^6Li (1.474 MeV). We used three nodes (minimum+1) for the α -cluster wave function of the 6.356 MeV $1/2^+$ state in ^{17}O (this excludes the node at the origin and infinity).

The combined uncertainty of the squared ANC was determined from statistical uncertainty, uncertainties in the normalization procedure, and from uncertainties associated with the dependence of the results on the number of wave functions nodes used and the optical potential parameters. If the potential parameters are kept within reasonable limits it was seen that the cross section varies by less than 15%. In fact even if the nuclear part of the potentials are removed the results only vary by about 30%. The total uncertainty calculated for this ANC is 19% and it is dominated by the optical potential parameters.

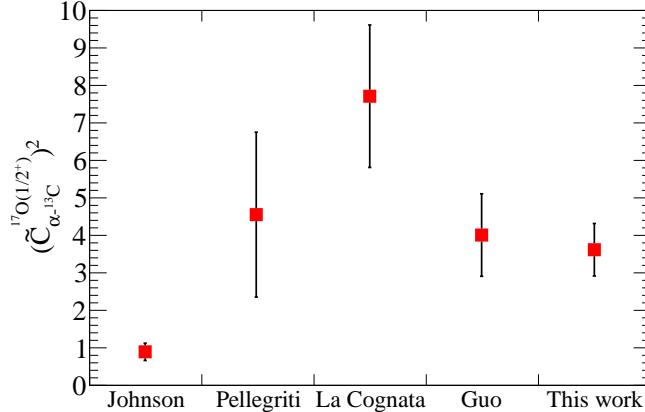


FIG. 4. Squared Coulomb modified ANC value obtained in this work, for the $1/2^+$ at excitation energy of 6.356 MeV in ^{17}O , compared to previous results from Johnson *et al.* [5], Pellegriti *et al.* [6], Cognata *et al.* [9] and Guo *et al.* [8].

III. RESULTS

The squared Coulomb modified ANC that we determined in this work for the $1/2^+$ state at 6.356 MeV in ^{17}O is $(\tilde{C}_{\alpha-13C}^{17O(1/2+)})^2 = 3.6 \pm 0.7 \text{ fm}^{-1}$. The ANCs reported in [5, 6, 8, 9] and the value obtained in this work are shown in Figure 4. In Table I a summary of the results for the squared Coulomb modified ANC values and spectroscopic factors S_α are shown. The ANC value of this work is within the error bars of the value found in [6, 8]. However, it is smaller than the value found using the Trojan Horse method in Ref. [9]. Compared to the ANC value obtained in the previous sub-Coulomb measurement in Ref. [5] the ANC obtained in this work is about 4 times larger. The reason for this discrepancy is explained below.

The cross section measured at the effective energy of 7.72 MeV in this work is compared to the cross section from Johnson *et al.* [5] at 7.81 MeV in Fig. 3. The cross section measured in [5] is about a factor of 3 smaller than the cross section measured in the present work. The main reason for this difference is the target deterioration effect that was not taken into account in Johnson *et al.* [5]. As mentioned above, the target thickening due to material buildup was observed in this experiment, causing the beam energy in the middle of the target to decrease. The effect was mitigated in this work by frequent target change and also by monitoring of the target condition using elastic scattering of ^6Li beam. This was

TABLE I. Summary of the previous and current results for the squared Coulomb modified ANC and spectroscopic factor S_α for the $1/2^+$ sub-threshold resonance at excitation energy of 6.356 MeV in ^{17}O .

$(\tilde{C}_{\alpha-^{13}\text{C}}^{^{17}\text{O}(1/2^+)})^2$ (fm^{-1})	S_α	Ref.
-	0.01	[3]
0.89 ± 0.23	-	[5]
-	0.36-0.40	[4]
4.5 ± 2.2	0.29 ± 0.11	[6]
$7.7 \pm 0.3_{\text{stat}} +1.6_{-1.5 \text{norm}}$	-	[9]
4.0 ± 1.1	0.37 ± 0.12	[8]
3.6 ± 0.7	-	This work

not done in the previous experiment [5]. Therefore, the beam energy in the middle of the target was decreasing during measurements that used the same target over extended period of time in Ref. [5]. As a result the measured cross section is significantly lower than it should have been. One of the characteristic features of sub-Coulomb transfer reactions (unlike the reactions performed at higher energies) is strong dependence of the reaction cross section on the energy of the beam. The lower reaction cross section measured in [5] naturally lead to the smaller ANC.

The importance of accurate knowledge of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction rate has been emphasized recently in Refs. [8, 9]. This report provides a more precise and almost model independent value for the ANC of the $1/2^+$ state at 6.356 MeV in ^{17}O . The ANC for this state is the most important parameter that determines the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction rate at energies relevant for the s-process in AGB stars. This calls for a new complete R-matrix analysis of all available experimental data that leads to ^{17}O (of the type performed in Ref. [7]) to determine the new “recommended” $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction rate. We expect that the new, small uncertainty for the $1/2^+$ at 6.356 MeV ANC value and also the new $^{13}\text{C}+\alpha$ elastic scattering data [18] at low energies will provide reliable reaction rate constraints that will be adequate for modern models of AGB stars. While this result does not eliminate the need for direct measurements of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction cross section at as low an energy as possible, it reduces the nuclear physics uncertainties of the s-process dramatically. It is

important to point out that this result also resolves the ambiguities arising from previous experimental results.

IV. SUMMARY

In summary, we used the direct α -transfer reaction ${}^6\text{Li}({}^{13}\text{C}, d){}^{17}\text{O}$ at a sub-Coulomb energy to extract the α ANC for the $1/2^+$ state at 6.356 MeV in ${}^{17}\text{O}$. This parameter is the major source of uncertainty for the astrophysically important ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ reaction rate at temperatures relevant for the s-process in AGB stars (<100 MK). The Coulomb modified squared ANC was determined to be $(\tilde{C}_{\alpha-{}^{13}\text{C}}^{17\text{O}(1/2^+)})^2 = 3.6 \pm 0.7 \text{ fm}^{-1}$. This is the most precise value to date but in good agreement with the results of Refs. [6, 8]. The main value of this work is that the discrepancy between the present results obtained by α -transfer reactions at higher energy and the sub-Coulomb energies is now removed. Both give similar values but the advantage of sub-Coulomb transfer is that this technique is much less model dependent. The discrepancy (although a much smaller one than before) still remains between the THM measurements and the sub-Coulomb ANC results. It is important to investigate the source of this discrepancy further in order to increase the reliability of both indirect methods, that promise to be important tools for nuclear astrophysics. The more accurate ANC for the $1/2^+$ at 6.356 MeV state in ${}^{17}\text{O}$ and the new low energy $\alpha+{}^{13}\text{C}$ elastic scattering data [18] can now be used to impose tighter constraints than before on the ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ reaction rate.

ACKNOWLEDGMENTS

The authors acknowledge the financial support provided by the National Science Foundation (USA) under grant No. PHY-456463. G.V.R and E.K. acknowledge that this material is based upon their work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Science, under Award No. DE-FG02-93ER40773. G.V.R also acknowledges the financial support of the Welch Foundation (USA) (Grant No.: A-1853).

[1] A. G. W. Cameron, *Astrophys. J* **121**, 144 (1955).

[2] I. Iben and A. Renzini, *Ann. Rev. Astron. Astrophys.* **21**, 271 (1983).

- [3] S. Kubono, K. Abe, S. Kato, T. Teranishi, M. Kurokawa, X. Liu, N. Imai, K. Kumagai, P. Strasser, M. H. Tanaka, Y. Fuchi, C. S. Lee, Y. K. Kwon, L. Lee, J. H. Ha, and Y. K. Kim, *Phys. Rev. Lett.* **90**, 062501 (2003).
- [4] N. Keeley, K. Kemper, and D. T. Khoa, *Nucl. Phys. A* **726**, 159 (2003).
- [5] E. D. Johnson, G. V. Rogachev, A. M. Mukhamedzhanov, L. T. Baby, S. Brown, W. T. Cluff, A. M. Crisp, E. Diffenderfer, V. Z. Goldberg, B. W. Green, T. Hinnens, C. R. Hoffman, K. W. Kemper, O. Momotyuk, P. Peplowski, A. Pipidis, R. Reynolds, and B. T. Roeder, *Phys. Rev. Lett.* **97**, 192701 (2006).
- [6] 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. Vilmy, *Phys. Rev. C* **77**, 042801 (2008).
- [7] M. Heil, R. Detwiler, R. E. Azuma, A. Couture, J. Daly, J. Görres, F. Käppeler, R. Reifarth, P. Tischhauser, C. Ugalde, and M. Wiescher, *Phys. Rev. C* **78**, 025803 (2008).
- [8] 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, *Astrophys. J* **756**, 193 (2012).
- [9] M. L. 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, *Astrophys. J* **777**, 143 (2013).
- [10] 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, *Phys. Rev. Lett.* **109**, 232701 (2012).
- [11] C. R. Brune, W. H. Geist, R. W. Kavanagh, and K. D. Veal, *Phys. Rev. Lett.* **83**, 4025 (1999).
- [12] M. L. Avila, G. V. Rogachev, E. Koshchiy, L. T. Baby, J. Belarge, K. W. Kemper, A. N. Kuchera, and D. Santiago-Gonzalez, *Phys. Rev. C* **90**, 042801(R) (2014).
- [13] M. L. Avila, G. V. Rogachev, E. Koshchiy, L. T. Baby, J. Belarge, K. W. Kemper, A. N. Kuchera, A. M. Mukhamedzhanov, D. Santiago-Gonzalez, and E. Uberseder, *Phys. Rev. Lett.* **114**, 071101 (2015).

- [14] M. L. Avila, *Clustering in ^{18}O and ANC measurements using $(^6\text{Li},d)$ reactions*, Ph.D. thesis, Florida State University (2013).
- [15] C. E. Rolfs, *Cauldrons in the Cosmos: Nuclear Astrophysics*, Vol. 1 (University of Chicago Press, 1988).
- [16] I. Thompson, *Comp. Phys. Rep.* **7**, 167 (1988).
- [17] K.-I. Kubo and M. Hirata, *Nucl. Phys. A* **187**, 186 (1972).
- [18] N. Mynbayev, A. Nurmukhanbetova, V. Goldberg, M. Golovkov, G. Rogachev, V. Dzyubin, M. Koloberdin, I. Ivanov, and R. Tribble, *Journal of Experimental and Theoretical Physics* **119**, 663 (2014).