Resolution of a long-standing discrepancy in the ^{17}O+^{12}C fusion excitation function

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There has been a long-standing discrepancy between existing measurements of the total fusion cross section for the ^{17}O + ^{12}C system at $E_{\text{c.m.}} \sim 14$ MeV. In order to resolve this inconsistency, the cross section was measured in two overlapping energy ranges using an ^{17}O beam and the *Encore* active target detector at Florida State University. *Encore* is a self-normalizing detector that measures a large portion of the fusion excitation function with a single beam energy. It also provides full angular coverage of the measured evaporation residues, thus ensuring a model independent measurement of the total fusion cross section. The data reported here show an oscillatory structure not previously observed in this system and agree with all previously reported measurements, resolving the long-standing discrepancy. Coupled reaction channels calculations reproduce the data except in the region of the the oscillation, which matches a similar structure seen in the ^{16}O + ^{12}C total fusion excitation function.

I. INTRODUCTION

Measurements of the fusion cross section at energies around the Coulomb barrier provide insight into the quantum many-body interaction and allow an exploration of the different mechanisms, such as breakup and transfer reactions, that define the structural properties of the fusion excitation function [1]. Phenomena like enhancement and hindrance of the cross section are currently being investigated using stable and radioactive beams. Such effects are crucial for understanding the fusion process which plays an important role in, for example, astrophysical environments [2]. Several studies have shown that for systems involving weakly-bound nuclei the breakup and transfer mechanisms cause hindrance of the total fusion cross section at energies above the Coulomb barrier and enhancement below it [3–5]. A systematic investigation of these effects on the fusion cross section can be performed using the coupled channels approach, see e.g. Refs. [2, 5–7] for reviews on this subject.

Many fusion systems can be reasonably reproduced by the coupled channels approach. However, different interpretations are needed in the case of light symmetric or near symmetric systems where oscillatory structures in the fusion excitation function at energies above the Coulomb barrier have been observed. These oscillations are prominent in the ^{12}C + ^{12}C, ^{16}O + ^{16}O, and ^{12}C + ^{16}O systems [8–10]. They have also been observed in ^{20}Ne + ^{20}Ne [11] and, recently, there is evidence of their existence in ^{28}Si + ^{28}Si [12]. Such features have been explained as due to a coupling effect of successive partial waves entering the fusion cross section as their centrifugal barriers are exceeded [11, 13, 14] or by using an effective model with an energy dependent barrier [15].

An interesting case for benchmarking our understanding of the fusion process is provided by the ^{17}O + ^{12}C system. The ^{17}O nucleus may be thought of as a ^{16}O core with a valence neutron in the $d_{5/2}$ orbital and is the mirror of the halo nucleus ^{17}F. The total fusion excitation function of the exotic ^{17}F + ^{12}C system has been shown to be smoothly varying within experimental error at energies above the Coulomb barrier [16, 17], despite the underlying ^{16}O core and the known oscillations and resonances in the ^{16}O + ^{12}C system. Moreover, the fusion excitation function of the ^{17}O + ^{12}C system is of particular interest because of a discrepancy in the published data that occurs at the energy of a known resonance in the ^{16}O + ^{12}C system [18]. It therefore seems timely to revisit the ^{17}O + ^{12}C total fusion excitation function to attempt to resolve the apparent discrepancy between the published data sets.

In this work we present a measurement of the ^{12}C + ^{17}O total fusion excitation function for energies above the Coulomb barrier using a ^{17}O beam and the Encore active target detector at Florida State University (FSU). Previous data show a striking discrepancy marked by a sharp discontinuity between the data of Hertz *et al.* [19] and Eyal *et al.* [20] at around $E_{\text{c.m.}} = 14$ MeV, see Fig. 1. Our experimental results span both data sets and show a large oscillation in the cross section that puts all data sets in agreement. This oscillation is comparable in size with the observed resonances in the even-even systems discussed above.

II. EXPERIMENTAL DETAILS

The experiment was performed at the John D. Fox accelerator laboratory at Florida State University (FSU). A ^{17}O beam was extracted from the SNICS ion source then accelerated by the tandem Van de Graaff and deliv-

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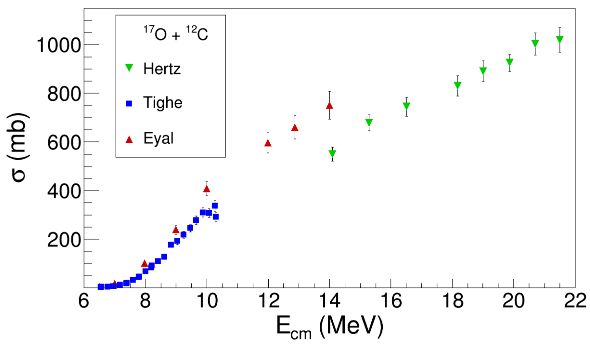

FIG. 1. Existing data for the ^{17}O + ^{12}C fusion excitation function from Refs. [19–21]. The data sets of Hertz *et al.* [21] and Tighe *et al.* [19] exhibit a discrepancy at $E_{\rm c.m.} = 14$ MeV of about 200 mb.

ered to the *Encore* active target detector at two different energies, 65 MeV and 55 MeV.

Encore is a multi-sampling ionization chamber (MUSIC) type active target detector developed at FSU and has been successfully used to measure fusion cross sections of stable ^{16}O and ^{19}F [22] and radioactive ^{17}F beams on ^{12}C [16] using CH_4 as the counting gas. *Encore* has also been used to measure cross sections of the $^{18}O(\alpha,p)$ and $^{18}O(\alpha,n)$ reactions using helium as counting gas [22]. A similar MUSIC-type detector has been used to measure various other reactions at Argonne National Laboratory (ANL) [23–26]. A full description of *Encore* is given in Ref. [16].

For the present experiment *Encore* was filled with CH_4 as counting gas with the carbon of the methane furnishing the target. The gains in the detector were set such that reactions with the hydrogen in the methane were not observed. The ^{17}O beam passed through a 2.11 mg/cm^2 HAVAR window and a 3 cm "dead" layer of CH_4 gas before entering the active region of the detector. *Encore* measures energy losses of the beam and the reaction products in a segmented anode. The anode is segmented into 18 distinct strips allowing for an energy loss measurement in 18 different regions within the detector. Two different beam energies and gas pressures were employed. Firstly, a 65 MeV ^{17}O beam was delivered to the detector filled with CH_4 gas at 154 Torr, resulting in a measurement of the fusion excitation function over the range $E_{\rm c.m.}$ = 20.4 - 12.1 MeV with an average energy of 0.8 MeV deposited in each strip. Secondly, the ^{17}O beam was delivered at 55 MeV to the detector filled with CH_4 gas at 126 Torr, resulting in a measurement of the fusion excitation function over the range $E_{\rm c.m.}$ = 16.3 - 8.7 MeV with an average energy of 0.7 MeV deposited in each strip. Both energies were delivered to the detector at a rate of about 10,000 pps. These settings were chosen in order to resolve the discrepancy between the data sets of Refs. [20, 21] and provide overlapping data points between $\sim$ 12 - 16 MeV in the center of mass of the ^{17}O + ^{12}C system.

III. RESULTS AND DISCUSSION

Total fusion events resulting in compound nucleus formation and evaporation residues (ERs) in *Encore* are identified within a strip by a characteristic ΔE "jump" and consequent signals relative to the Bragg curve of the beam as it passes through the detector. The detector is not sensitive to light particle evaporation coming from the ERs. A thorough description of the analysis procedure is given in Ref. [16]. These events are normalized by the number of beam events registered within the same strip. The absolute total fusion cross section is then determined by calculating the density of carbon 'targets' within the thickness of a strip (1.5 cm) in the detector. The reported error bars in the cross section measurements are statistical and are on average about $\pm 8\%$. The energy values in each strip are assigned using an energy loss calculation for the beam in each strip of the detector performed with LISE++ [27]. The initial beam energy for a stable beam is set by the analyzing magnet in the accelerator beam line and it is confirmed after the entrance window by a silicon detector mounted at the back of *Encore*, used for tuning the beam without gas in the detector. The energy points are taken to be the values at the center of the strips. Error bars in the energy are given by the size of the strip.

The fusion cross sections measured in this experiment are plotted in Fig. 2 and listed in Table I. Our results show a large structure in the fusion excitation function of the ^{17}O + ^{12}C system around $E_{\rm c.m.} = 13 - 15$ MeV, followed by one or two smaller structures between $E_{\rm c.m.} = 14 - 20$ MeV. The overlapping data points from the two sets of measurements with different beam energies and gas pressures confirm these structures. As Fig. 2 shows, the new data reconcile the large differences between the previous measurements and all four existing data sets (the present measurement plus the data of Refs. [19–21]) agree within experimental errors where they overlap.

In order further to investigate these results, coupled reaction channel (CRC) calculations were carried out using the code FRESCO [28]. Couplings included inelastic excitation of the 4.44-MeV 2^+ excited state of the ^{12}C, with the $B(E2)$ taken from Raman *et al.* [29] and the nuclear deformation length, $\delta_2 = -1.40$ fm, from Ref. [30]; inelastic excitation of the 0.87-MeV $1/2^+$ first excited state of ^{17}O, with the $B(E2)$ taken from Ref. [31] and the $\delta_2 = 1.20$ fm from Ref. [32]; and the $^{12}C(^{17}O,^{16}O)^{13}C$ single-neutron transfer reaction. Excitation of the 6.13-MeV 3^- level of ^{16}O was also included in the exit partition, with the $B(E3)$ taken from Ref. [33] and $\delta_3 = 1.71$ fm from Ref. [32]. The various overlaps, together with the spectroscopic amplitudes used are listed in Table II. Note that due to the matching conditions and the relatively low incident energies involved single-neutron trans-

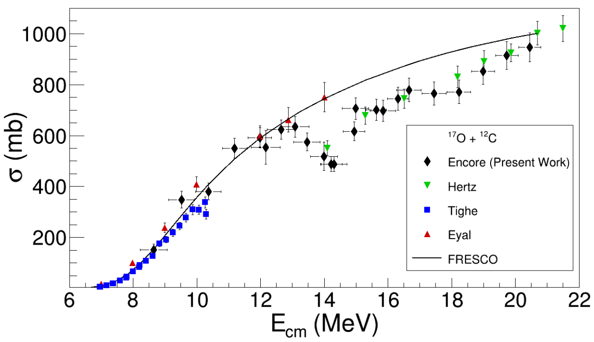

FIG. 2. Experimental total fusion cross sections for the ^{17}O + ^{12}C system measured with *Encore* compared with the existing data from Refs. [19–21]. Good agreement is seen between all four sets. The solid line represents a coupled reaction channel calculation carried out using FRESCO which included couplings to the first excited states of ^{12}C and ^{17}O as well as the ^{12}C(^{17}O,^{16}O)^{13}C single-neutron transfer reaction.

$E_{\rm c.m.}$ (MeV)	σ (mb)	$E_{\rm c.m.}$ (MeV)	σ (mb)
20.5 ± 0.3	946 ± 57	14.2 ± 0.3	489 ± 29
19.7 ± 0.4	914 ± 55	14.0 ± 0.4	519 ± 56
19.0 ± 0.4	852 ± 51	13.5 ± 0.4	574 ± 34
18.2 ± 0.4	771 ± 46	13.1 ± 0.4	635 ± 41
17.5 ± 0.4	765 ± 46	12.6 ± 0.4	624 ± 37
16.7 ± 0.4	779 ± 47	12.2 ± 0.5	554 ± 66
16.3 ± 0.3	744 ± 45	12.0 ± 0.4	591 ± 39
15.8 ± 0.4	698 ± 42	11.2 ± 0.4	551 ± 39
15.6 ± 0.3	701 ± 42	10.4 ± 0.4	380 ± 34
15.0 ± 0.4	706 ± 42	9.5 ± 0.4	349 ± 34
14.9 ± 0.3	617 ± 37	8.7 ± 0.4	151 ± 24
14.3 ± 0.4	488 ± 29		

TABLE I. Total fusion cross sections for the ^{17}O + ^{12}C system measured in the present experiment with *Encore* as a function of the center-of-mass energy.

TABLE II. Overlaps plus corresponding spectroscopic amplitudes (S) and shell model level ($n\ell_j$) included in the CRC calculations. The signs of the spectroscopic amplitudes are consistent with the phase convention used in FRESCO.

Overlap	S	$n\ell_j$	Ref.
$\langle ^{17}\mathrm{O}(5/2^+) \mid ^{16}\mathrm{O}(0^+) + n \rangle$	0.972	$1d_{5/2}$	[34]
$\langle ^{17}\mathrm{O}(5/2^+) \mid ^{16}\mathrm{O}(3^-) + n \rangle$	−0.718	$1p_{1/2}$	[34]
$\langle ^{17}\mathrm{O}(1/2^+) \mid ^{16}\mathrm{O}(0^+) + n \rangle$	0.975	$1s_{1/2}$	[34]
$\langle ^{13}\mathrm{C}(1/2^-) \mid ^{12}\mathrm{C}(0^+) + n \rangle$	0.601	$1p_{1/2}$	[35]
$\langle ^{13}\mathrm{C}(1/2^-) \mid ^{12}\mathrm{C}(2^+) + n \rangle$	1.124	$1p_{3/2}$	[35]
$\langle ^{13}\mathrm{C}(1/2^+) \mid ^{12}\mathrm{C}(0^+) + n \rangle$	0.957	$2s_{1/2}$	[36]
$\langle ^{13}\mathrm{C}(1/2^+) \mid ^{12}\mathrm{C}(2^+) + n \rangle$	0.291	$1d_{5/2}$	[36]
$\langle ^{13}\mathrm{C}(3/2^-) \mid ^{12}\mathrm{C}(0^+) + n \rangle$	0.601	$1p_{3/2}$	[35]
$\langle ^{13}\mathrm{C}(3/2^-) \mid ^{12}\mathrm{C}(2^+) + n \rangle$	−0.745	$1p_{1/2}$	[35]
$\langle ^{13}\mathrm{C}(3/2^-) \mid ^{12}\mathrm{C}(2^+) + n \rangle$	−0.745	$1p_{3/2}$	[35]
$\langle ^{13}\mathrm{C}(5/2^+) \mid ^{12}\mathrm{C}(0^+) + n \rangle$	0.550	$1d_{5/2}$	[37]

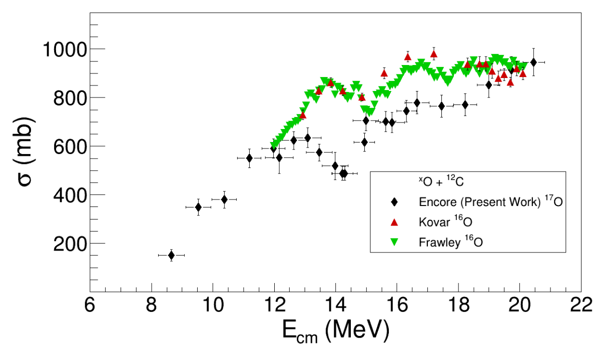

FIG. 3. Experimental fusion cross sections for the ^{17}O + ^{12}C system measured with *Encore* plotted together with existing ^{16}O + ^{12}C data that show oscillatory structure [9, 46]. A large resonance-type feature is seen in the ^{16}O + ^{12}C total fusion cross section at $E_{\rm c.m.} \approx 14$ MeV.

fer leaving the ^{16}O in its 6.13-MeV 3^- level was only included for the transition to the ^{13}C $1/2^-$ ground state.

The real parts of the input optical model potentials were calculated within the double-folding framework with the M3Y nucleon-nucleon effective interaction [38] using the code DFPOT [39]. The required ^{12}C, ^{17}O, ^{13}C, and ^{16}O nuclear matter densities were derived from the experimental charge densities of Refs. [40], [41], [42], and [43], respectively by unfolding the proton charge density and assuming that $\rho_{\rm Nuc} = (1 + N/Z)\rho_p$. The imaginary parts of the optical potentials were of Woods-Saxon squared form, with depth $W = 50$ MeV, radius $R_W = 1.0 \times (\mathrm{A}_p^{1/3} + \mathrm{A}_t^{1/3})$ fm and diffuseness $a_W = 0.3$ fm, effectively reproducing the incoming wave boundary condition [44]. In this model the total fusion cross section is defined as the sum of the absorption by the imaginary parts of the potentials in all channels and is thus the difference between the reaction cross section and the sum of the integrated cross sections for all channels included in the coupling scheme.

As can be seen in Fig. 2, the data for $E_{\rm c.m.} < 13$ MeV and > 20 MeV are reproduced quite well by the CRC calculation. However, the data fall below the theoretical curve at energies $E_{\rm c.m.} = 13$ - 20 MeV and the structure at $E_{\rm c.m.} = 14$ MeV is not reproduced. Similar behavior was observed in the ^{13}C + ^{12}C system where the total fusion data also fall below the prediction of CRC calculations including the elastic and inelastic transfer couplings for energies $E_{\rm c.m.} > 13$ MeV [45], although the ^{13}C + ^{12}C data do not exhibit any marked oscillations. A possible explanation may lie in the structure measured by Taras *et al.* [18] in various exit channels of the ^{16}O + ^{12}C reaction in a similar energy region causing constructive and destructive interference resulting from a ^{16}O + n + ^{12}C type configuration. The large "elbow" at $E_{\rm c.m.} = 14$ MeV could thus be related to the well known oscillatory behavior of the fusion cross section in the ^{16}O + ^{12}C system [9]. To highlight this, Fig. 3 plots existing ^{16}O + ^{12}C total fusion data from Refs. [9, 46] together with the present ^{17}O + ^{12}C measurement. A large resonance is observed in the ^{16}O data in the same energy region of $E_{\rm c.m.}$ = 14 MeV as for ^{17}O. If the observed structure in the ^{17}O + ^{12}C total fusion excitation function is indeed linked to resonant-like behavior in the underlying ^{16}O + ^{12}C system then conventional CRC calculations would not be expected to be able to reproduce the data in the energy region concerned, since such effects cannot be included in the standard formalism.

IV. SUMMARY

The ^{17}O + ^{12}C total fusion cross section was measured with *Encore*, an active target detector that measures a large portion of the fusion excitation function using a single beam energy with absolute self-normalization and full angular coverage of evaporation residues, in order to resolve a long-standing discrepancy at around $E_{\rm c.m.} \sim 14$ MeV where previous data differ by a large factor not explained by the experimental error bars. The measurement was performed using two sets of beam energy and gas pressure to map out the energy region $E_{c.m.}$ = 8.7 - 20.4 MeV with overlapping data between 12 - 16 MeV, spanning all the existing data sets.

Our results show a large oscillatory-like structure, not previously observed, in the region of the discrepancy between the data of Refs. [20] and [21], reconciling the two data sets within their respective experimental errors. Similar behavior has been seen in the ^{16}O + ^{16}O [10], ^{16}O + ^{12}C [9], and ^{12}C + ^{12}C [8] fusion excitation functions. Coupled reaction channel calculations including couplings to excited states of ^{17}O and ^{12}C as well as the ^{12}C(^{17}O,^{16}O)^{13}C single-neutron transfer reaction described the data well for energies $E_{\rm c.m.} < 13$ MeV and > 20 MeV but were unable to reproduce the structure at around $E_{\rm c.m.} \sim 14$ MeV.

Taking the above considerations into account, it seems likely that the newly observed structure in the ^{17}O + ^{12}C total fusion excitation function is linked to resonance-like features in the ^{16}O + ^{12}C total fusion data [9, 46], suggesting the formation of a ^{16}O + n + ^{12}C type configuration.

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[1] M. Dasgupta, D. J. Hinde, N. Rowley, and A. M. Stefanini. Measuring barriers to fusion. *Annual Review of Nuclear and Particle Science*, 48(1):401–461, 1998.

[2] J. J. Kolata, V. Guimarães, and E. F. Aguilera. Elastic scattering, fusion, and breakup of light exotic nuclei. *The European Physical Journal A*, 52(123), 2016.

[3] A. Lemasson, A. Shrivastava, A. Navin, M. Rejmund, N. Keeley, V. Zelevinsky, S. Bhattacharyya, A. Chatterjee, G. de France, B. Jacquot, V. Nanal, R. G. Pillay, R. Raabe, and C. Schmitt. Modern rutherford experiment: Tunneling of the most neutron-rich nucleus. *Phys. Rev. Lett.*, 103:232701, Nov 2009.

[4] G. S. Li, J. G. Wang, J. Lubian, H. O. Soler, Y. D. Fang, M. L. Liu, N. T. Zhang, X. H. Zhou, Y. H. Zhang, B. S. Gao, Y. H. Qiang, S. Guo, S. C. Wang, K. L. Wang, K. K. Zheng, R. Li, and Y. Zheng. Fusion reactions in the ^{9}Be+^{197}Au system above the coulomb barrier. *Phys. Rev. C*, 100:054601, Nov 2019.

[5] N. Keeley, R. Raabe, N. Alamanos, and J.L. Sida. Fusion and direct reactions of halo nuclei at energies around the coulomb barrier. *Progress in Particle and Nuclear Physics*, 59(2):579 – 630, 2007.

[6] J. F. LIANG and C. SIGNORINI. Fusion induced by radioactive ion beams. *International Journal of Modern Physics E*, 14(08):1121–1150, 2005.

[7] L.F. Canto, P.R.S. Gomes, R. Donangelo, and M.S. Hussein. Fusion and breakup of weakly bound nuclei. *Physics Reports*, 424(1):1–111, 2006.

[8] P. Sperr, T. H. Braid, Y. Eisen, D. G. Kovar, F. W. Prosser, J. P. Schiffer, S. L. Tabor, and S. Vigdor. Fusion cross sections of light heavy-ion systems: Resonances and shell effects. *Phys. Rev. Lett.*, 37:321–323, Aug 1976.

[9] D. G. Kovar, D. F. Geesaman, T. H. Braid, Y. Eisen, W. Henning, T. R. Ophel, M. Paul, K. E. Rehm, S. J. Sanders, P. Sperr, J. P. Schiffer, S. L. Tabor, S. Vigdor, B. Zeidman, and F. W. Prosser. Systematics of carbon- and oxygen-induced fusion on nuclei with $12 \leq a \leq 19$. *Phys. Rev. C*, 20:1305–1331, Oct 1979.

[10] I. Tserruya, Y. Eisen, D. Pelte, A. Gavron, H. Oeschler, D. Berndt, and H. L. Harney. Total fusion cross section for the ^{16}O+^{16}O system. *Phys. Rev. C*, 18:1688–1699, Oct 1978.

[11] N. Poffe, N. Rowley, and R. Lindsay. Fusion oscillations for symmetric light heavy-ion systems. *Nuclear Physics A*, 410(3):498–512, 1983.

[12] G. Montagnoli, A.M. Stefanini, H. Esbensen, L. Corradi, S. Courtin, E. Fioretto, J. Grebosz, F. Haas, H.M. Jia, C.L. Jiang, M. Mazzocco, C. Michelagnoli, T. MijatoviÄ‡, D. Montanari, C. Parascandolo, F. Scarlassara, E. Strano, S. Szilner, and D. Torresi. Oscillations above the barrier in the fusion of 28si + 28si. *Physics Letters B*, 746:300–304, 2015.

[13] H. Esbensen. Structures in high-energy fusion data. *Phys. Rev. C*, 85:064611, Jun 2012.

[14] C. Simenel, R. Keser, A. S. Umar, and V. E. Oberacker. Microscopic study of ^{16}O + ^{16}O fusion. *Phys. Rev. C*, 88:024617, Aug 2013.

[15] N. Rowley and K. Hagino. Examination of fusion cross sections and fusion oscillations with a generalized wong formula. *Phys. Rev. C*, 91:044617, Apr 2015.

[16] B. W. Asher, S. Almaraz-Calderon, Vandana Tripathi, K. W. Kemper, L. T. Baby, N. Gerken, E. Lopez-Saavedra, A. B. Morelock, J. F. Perello, I. Wiedenhöver, and N. Keeley. Experimental study of the ^{17}F +^{12} C fusion reaction and its implications for fusion of proton-halo systems. *Phys. Rev. C*, 103:044615, Apr 2021.

[17] Varinderjit Singh, J. Vadas, T. K. Steinbach, B. B. Wiggins, S. Hudan, and R. T. deSouza. Assessing the impact of valence *sd* neutrons and protons on fusion. *Phys. Rev. C*, 103:064606, Jun 2021.

[18] P. Taras, G. Rao, N. Schulz, J. P. Vivien, B. Haas, J. C. Merdinger, and S. Landsberger. Resonance at $E_{\text{c.m.}} =$ 12.8 mev in the ^{12}C + ^{16}O system. *Phys. Rev. C*, 15:834–836, Feb 1977.

[19] R. J. Tighe, J. J. Kolata, M. Belbot, and E. F. Aguilera. Possible signatures of nuclear-molecular formation in o+c systems. *Phys. Rev. C*, 47:2699–2716, Jun 1993.

[20] Y. Eyal, M. Beckerman, R. Chechik, Z. Fraenkel, and H. Stocker. Nuclear size and boundary effects on the fusion barrier of oxygen with carbon. *Phys. Rev. C*, 13:1527–1535, Apr 1976.

[21] A. Hertz, H. Essel, H. J. Körner, K. E. Rehm, and P. Sperr. Maximum fusion cross section for the system ^{12}C + ^{17}O. *Phys. Rev. C*, 18:2780–2781, Dec 1978.

[22] B. W. Asher, S. Almaraz-Calderon, L. T. Baby, N. Gerken, E. Lopez-Saavedra, A. B. Morelock, and J. F. Perello. The encore active target detector: a multi-sampling ionization chamber. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Submitted for Publication.

[23] P. F. F. Carnelli, S. Almaraz-Calderon, K. E. Rehm, M. Albers, M. Alcorta, P. F. Bertone, B. Digiovine, H. Esbensen, J. O. Fernández Niello, D. Henderson, C. L. Jiang, J. Lai, S. T. Marley, O. Nusair, T. Palchan-Hazan, R. C. Pardo, M. Paul, and C. Ugalde. Measurements of fusion reactions of low-intensity radioactive carbon beams on ^{12}C and their implications for the understanding of x-ray bursts. *Phys. Rev. Lett.*, 112:192701, 2014.

[24] M. L. Avila, K. E. Rehm, S. Almaraz-Calderon, A. D. Ayangeakaa, C. Dickerson, C. R. Hoffman, C. L. Jiang, B. P. Kay, J. Lai, O. Nusair, R. C. Pardo, D. Santiago-Gonzalez, R. Talwar, and C. Ugalde. Experimental study of the astrophysically important ^{23}Na$(\alpha,p)^{26}$Mg and ^{23}Na$(\alpha,n)^{26}$Al reactions. *Phys. Rev. C*, 94:065804, Dec 2016.

[25] M.L. Avila, K.E. Rehm, S. Almaraz-Calderon, A.D. Ayangeakaa, C. Dickerson, C.R. Hoffman, C.L. Jiang, B.P. Kay, J. Lai, O. Nusair, R.C. Pardo, D. Santiago-Gonzalez, R. Talwar, and C. Ugalde. Study of (α,p) and (α,n) reactions with a multi-sampling ionization chamber. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 859:63 – 68, 2017.

[26] P.F.F. Carnelli, S. Almaraz-Calderon, K.E. Rehm, M. Albers, M. Alcorta, P.F. Bertone, B. Digiovine, H. Esbensen, J. Fernández Niello, D. Henderson, C.L. Jiang, J. Lai, S.T. Marley, O. Nusair, T. Palchan-Hazan, R.C. Pardo, M. Paul, and C. Ugalde. Multi-sampling ionization chamber (music) for measurements of fusion reactions with radioactive beams. *Nuclear Instruments*

and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 799:197 – 202, 2015.

[27] O. B. Tarasov and D. Bazin. LISE++: Radioactive beam production with in-flight separators. *Nuclear Instruments and Methods in Physics Research B*, 266(19-20):4657–4664, October 2008.

[28] Ian J. Thompson. Coupled reaction channels calculations in nuclear physics. *Computer Physics Reports*, 7(4):167–212, 1988.

[29] S. Raman, C.W. Nestor, and P. Tikkanen. Transition probability from the ground to the first-excited 2+ state of even-even nuclides. *Atomic Data and Nuclear Data Tables*, 78(1):1–128, 2001.

[30] N. Keeley, K. W. Kemper, and K. Rusek. Strong multistep interference effects in ^{12}C(d, p) to the $9/2^+_1$ state in ^{13}C. *Phys. Rev. C*, 92:054618, Nov 2015.

[31] D. M. Manley, B. L. Berman, W. Bertozzi, T. N. Buti, J. M. Finn, F. W. Hersman, C. E. Hyde-Wright, M. V. Hynes, J. J. Kelly, M. A. Kovash, S. Kowalski, R. W. Lourie, B. Murdock, B. E. Norum, B. Pugh, and C. P. Sargent. High-resolution inelastic electron scattering from ^{17}O. *Phys. Rev. C*, 36:1700–1726, Nov 1987.

[32] E. Strano, D. Torresi, M. Mazzocco, N. Keeley, A. Boiano, C. Boiano, P. Di Meo, A. Guglielmetti, M. La Commara, P. Molini, C. Manea, C. Parascandolo, D. Pierroutsakou, C. Signorini, F. Soramel, D. Filipescu, A. Gheorghe, T. Glodariu, J. Grebosz, S. Jeong, Y. H. Kim, J. A. Lay, H. Miyatake, M. Nicoletto, A. Pakou, K. Rusek, O. Sgouros, V. Soukeras, L. Stroe, N. Toniolo, A. Vitturi, Y. Watanabe, and K. Zerva. ^{17}O +^{58} Ni scattering and reaction dynamics around the coulomb barrier. *Phys. Rev. C*, 94:024622, Aug 2016.

[33] T Kibédi and R.H Spear. Reduced electric-octupole transition probabilities, b(e3;$0^+_1 \rightarrow 3^-_1$)-an update. *Atomic Data and Nuclear Data Tables*, 80(1):35–82, 2002.

[34] M. Cavallaro, F. Cappuzzello, M. Bondì, D. Carbone, V. N. Garcia, A. Gargano, S. M. Lenzi, J. Lubian, C. Agodi, F. Azaiez, M. De Napoli, A. Foti, S. Franchoo, R. Linares, D. Nicolosi, M. Niikura, J. A. Scarpaci, and S. Tropea. Quantitative analysis of two-neutron correlations in the ^{12}c(^{18}o,^{16}o)^{14}c reaction. *Phys. Rev. C*, 88:054601, Nov 2013.

[35] V.A. Ziman, A.T. Rudchik, A. Budzanowski, V.K. Chernievsky, L. Glowacka, E.I. Koshchy, S. Kliczewski, M. Makowska-Rzeszutko, A.V. Mokhnach, O.A. Momotyuk, O.A. Ponkratenko, R. Siudak, I. Skwirczynska, A. Szczurek, and J. Turkiewicz. Channel couplings in the 12c(14n,x) reactions at e(14n) = 116 mev. *Nuclear Physics A*, 624(3):459–471, 1997.

[36] A. A. Rudchik, A. T. Rudchik, G. M. Kozeratska, O. A. Ponkratenko, E. I. Koshchy, A. Budzanowski, B. Czech, S. Kliczewski, R. Siudak, I. Skwirczyńska, A. Szczurek, S. Yu. Mezhevych, K. W. Kemper, J. Choiński, T. Czosnyka, and L. Głowacka. ^{7}Li +^{11} B elastic and inelastic scattering in a coupled-reaction-channels approach. *Phys. Rev. C*, 72:034608, Sep 2005.

[37] A.T Rudchik, O.A Momotyuk, A Budzanowski, A Szczurek, V.K Chernievsky, A.V Mokhnach, V.A Ziman, E.I Koshchy, S Kliczewski, R Siudak, I Skwirczynska, and J Turkiewicz. Energy dependence of the 8be + 13c interaction. *Nuclear Physics A*, 660(3):267–279, 1999.

[38] G.R. Satchler and W.G. Love. Folding model potentials from realistic interactions for heavy-ion scattering. *Physics Reports*, 55(3):183–254, 1979.

[39] J. Cook. Dfpot - a program for the calculation of double folded potentials. *Computer Physics Communications*, 25(2):125–139, 1982.

[40] L.S. Cardman, J.W. Lightbody, S. Penner, S.P. Fivozinsky, X.K. Maruyama, W.P. Trower, and S.E. Williamson. The charge distribution of 12c. *Physics Letters B*, 91(2):203–206, 1980.

[41] R. P. Singhal, J. R. Moreira, and H. S. Caplan. Rms charge radii of ^{16,17,18}O by elastic electron scattering. *Phys. Rev. Lett.*, 24:73–75, Jan 1970.

[42] H. A. Bentz. Kernradien von ^{12}c,^{13}c,^{14}n und ^{16}o aus elektronenstreuung zwischen 30 und 60 mev. *Z. Physik*, 243:138, 1971.

[43] H. De Vries, C.W. De Jager, and C. De Vries. Nuclear charge-density-distribution parameters from elastic electron scattering. *Atomic Data and Nuclear Data Tables*, 36(3):495–536, 1987.

[44] M.J. Rhoades-Brown and P. Braun-Munzinger. Explanation of sub-barrier fusion enhancement in a coupled channels model. *Physics Letters B*, 136(1):19–23, 1984.

[45] Keeley, N., Kemper, K. W., and Rusek, K. Influence of halo single-neutron transfer on near barrier ^{15}c + ^{12}c total fusion. *Eur. Phys. J. A*, 57(5):168, 2021.

[46] A. D. Frawley, N. R. Fletcher, and L. C. Dennis. Resonances in the ^{16}O + ^{12}C fusion cross section between $E_{\text{c.m.}}$ = 12and20 mev. *Phys. Rev. C*, 25:860–865, Feb 1982.