Experimental study of the $^{17}$F+$^{12}$C fusion reaction and its implications for fusion of proton-halo systems

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, and I. Wiedenhöver

Department of Physics, Florida State University, Tallahassee, Florida 32306, USA

N. Keeley
National Centre for Nuclear Research, ul. Andrzeja Soltana 7, 05-400 Otwock, Poland

(Dated: October 13, 2020)

The halo nature of the low-lying $1/2^+$ first excited state of the exotic weakly-bound proton drip-line nucleus $^{17}$F has long been hypothesized. The structure of such a halo nucleus would imply special nuclear properties including, possibly, an enhancement in its fusion cross section above the barrier. The total fusion cross section of $^{17}$F + $^{12}$C near the Coulomb barrier was studied using the newly developed ‘Encore’ active-target detector at Florida State University. Total fusion cross sections for the stable counterpart systems $^{16}$O + $^{12}$C and $^{19}$F + $^{12}$C were also measured to enable a systematic comparison. No influence of the halo nature of the $^{17}$F 1/2$^+$ first excited state on its fusion excitation function was observed when compared with the stable counterpart systems.

I. INTRODUCTION

Fusion measurements are a key component of research in nuclear structure, nuclear reactions and nuclear astrophysics [1]. For example, the $^{12}$C + $^{14}$C fusion reaction determines the burning conditions and subsequent isotopic composition of the resulting ashes in massive stars [2]. Furthermore, in neutron-rich stars fusion of exotic carbon and oxygen isotopes may act as catalysts for the so called x-ray superbursts [3]. Recently, fusion reaction experiments involving light exotic beams have become the focus of several studies since such nuclei have become accessible at existing facilities. This area of research will only grow with the forthcoming exotic beam facilities around the world. Beams of short-lived radioactive nuclei present unique opportunities to probe the dynamics of fusion reactions around the Coulomb barrier. Weakly-bound light exotic nuclei in particular provide the possibility to explore the interplay between fusion, breakup and transfer reactions over a much wider range of binding energies and structural properties than those available with stable beams [4]. A specific sub-class of this type of nucleus are the so-called halo nuclei which have extended matter distributions [5] such that large breakup and/or transfer cross sections are observed at incident energies close to the Coulomb barrier [6].

It has long been suggested that the fusion cross section should be significantly enhanced in systems involving halo nuclei [8, 9] due to their extended size, since the fusion probability is highly dependent on the size and the shape of the interacting nuclei. On the other hand, due to their low threshold against breakup it has also been suggested that there could be significant suppression of fusion in such systems. However, the question of whether or not fusion in systems involving halo nuclei is enhanced has not yet been satisfactorily answered experimentally. In fact, fusion reactions involving halo nuclei have led to contradictory conclusions [4, 8–10] which could be the result of experimental uncertainties but also the lack of sufficient data for a systematic comparison between systems. A more fundamental problem is the lack of general agreement as to the benchmark used to infer enhancement or suppression and whether complete fusion or total fusion should be considered (see, e.g., Ref. [4] for a discussion of these questions).

Most experiments with halo nuclei have been carried out on the neutron-rich side of the chart of the nuclides [4]. Results of fusion reactions with the neutron-rich halo nuclei $^6$He [11–12], $^{11}$Li [13] and $^{11}$Be [14–15] show an effect on the fusion excitation function which is mainly manifested as a reduction in the cross section above the barrier. This effect has been explained by the low breakup threshold of these systems [10], resulting in the loss of beam flux at relatively large distances between the colliding nuclei due to breakup itself and/or neutron transfer reactions.

For proton-halo nuclei, despite the expanded size of the halo their weakly-bound nature might also be expected to manifest itself as a reduction of the fusion cross section above the Coulomb barrier [10–16]. However, the few available experimental results appear inconsistent. For example, the proton-halo nucleus $^8$B has been the object of various studies with $^{58}$Ni and $^{28}$Si [17–18] targets. The $^8$B + $^{58}$Ni system showed an enhancement in the fusion cross section in all regions including well above the Coulomb barrier while the $^8$B + $^{28}$Si system shows a slight suppression above the barrier [17–18].

The conclusions concerning the fusion of $^{17}$F, the focus of this work, are also not definitive. The $^{17}$F nucleus has a low breakup threshold ($S_p = 600$ keV) but since its ground state is usually deemed to consist of a proton in the 1d$_{3/2}$ shell outside the doubly magic $^{16}$O core it

* Email address: bwa15@my.fsu.edu

1 Email address: salmarazcalderon@fsu.edu
is not considered to constitute a halo due to the large centrifugal barrier. Rather, it is the low-lying 1/2 first excited state \( (E_{\text{exc}} = 105 \text{ keV}) \) with the “valence” proton in the \( 2n_{1/2} \) shell which is thought to be a proton halo \[19\]. The inherent nuclear structure of \(^{17}\)F therefore makes it a prime candidate for reaction studies and for investigating the effect on the fusion cross section of a possible proton halo in a low-lying bound excited state. There have been a few experimental studies using \(^{17}\)F beams \[20-22\]. One such study measured the fusion cross section for a \(^{208}\)Pb target where it was concluded that at energies around the Coulomb barrier no enhancement of the fusion cross section is observed \[9\], in contrast with the results for the \(^{8}\)B + \(^{58}\)Ni system \[17\] but consistent with those for \(^{8}\)B + \(^{28}\)Si \[18\]. It has been suggested that this lack of an enhancement in the fusion cross section could be due to an effective polarization of the \(^{17}\)F in the strong Coulomb field of the \(^{208}\)Pb target, leading to a shielding effect on the halo proton \[23\].

The present work reports a measurement of the fusion cross section excitation function for the \(^{17}\)F + \(^{12}\)C system at energies around the Coulomb barrier to search for the effects of its weak binding in a light mass system, thus obviating any possible shielding effects. A novel detector system developed at Florida State University allows for simultaneous detection of the incoming beam and the fusion products. The fusion products are measured simultaneously over an extended energy range without changing the energy of the incoming beam. The same experimental conditions were used to measure the fusion cross sections for the more tightly-bound stable systems \(^{16}\)O + \(^{12}\)C and \(^{19}\)F + \(^{12}\)C at energies near the Coulomb barrier, thus enabling a direct comparison of the fusion cross sections for all three systems.

II. EXPERIMENTAL DETAILS

The experiment was performed at the John D. Fox accelerator laboratory at Florida State University (FSU). A \(^{17}\)F radioactive beam was produced by the RESOLUT radioactive beam facility \[24\]. A stable \(^{16}\)O beam from the SNICS ion source was accelerated to 64.5 MeV by the tandem Van de Graaff accelerator and boosted to 91.5 MeV by the coupled LINAC accelerator. A liquid nitrogen cooled deuterium gas production target kept at a pressure of 350 torr was bombarded with the \(^{16}\)O beam. The radioactive \(^{17}\)F beam \((t_{1/2} = 64.5 \text{ s})\) was produced at a rate of \(\sim 600 \text{ particles per second} \text{ (pps)} \) in-flight via the \(^{16}\)O(d,n)\(^{17}\)F reaction and focused onto the detector system by the super conducting solenoid of RESOLUT. The main contaminant was the primary \(^{16}\)O beam at a rate of \(\sim 1100 \text{ pps}, \) which was used simultaneously in our experiment. A measurement with a stable \(^{19}\)F beam from the Tandem accelerator was also performed.

The 69.1 MeV \(^{17}\)F beam and its main contaminant, the 58.1 MeV \(^{16}\)O beam, were delivered to the \textit{Encore} active-target detector. \textit{Encore} is a multi-sampling ionization chamber recently developed at FSU, optimized to measure fusion cross sections with low-intensity exotic beams \((\lesssim 10 \text{ kHz})\). \textit{Encore} is based on the MUSIC detector at Argonne National Laboratory (ANL) \[25\]. Details of the \textit{Encore} detector will be published in a separate paper \[26\]. This detector system and analysis procedure has been successfully used at ANL for measurements of fusion reactions with carbon isotopes \[3\] as well as for measurements of \((\alpha,p)\) and \((\alpha,n)\) reactions \[27, 28\].

A schematic view of the \textit{Encore} detector is shown in the upper panel of Fig. 1. The beam enters through a 2.11 mg/cm\(^2\) HARVAR window. \textit{Encore} works as an ionization chamber with an electric field perpendicular to the beam axis and a segmented anode that measures energy losses as the beam passes through the detector.

For this experiment \textit{Encore} was filled with CH\(_2\) gas at 168 torr. After the beam enters the detector it travels 3 cm in a dead region before entering the segmented anode region. Energy losses of the beam are measured as it passes through the detector via 16 anode signals (strips 1, 2, \ldots, 16) subdivided into left and right as shown in the lower panel of Fig. 1. The 16 strips to the right and the left are independently read using two 16-channel MPR-16 pre-amplifiers connected with high density FGG lemo cables and added together in the analysis. Two extra anode signals at the beginning and the end of the detector (strips 0 and 17) are read individually and are used for vetoing and control. Signals from the cathode and the Frisch grid are also read out. The \(^{17}\)F and \(^{16}\)O beams are separated by their different time-of-flight and their different \(\Delta E\) signals as shown in the inset to Fig. 2.

The energy losses measured in each strip are analyzed on an event-by-event basis. One event through the detector, composed of 16 right side anode, 16 left side anode, 1 strip 0, and 1 strip 17 signals, is called a trace. Most of the time \textit{Encore} measures beam-like events. A sample of the experimental \(^{17}\)F beam traces is shown by the black lines in Fig. 2 where they were normalized to channel 500 for the analysis. Fusion-like events are characterized by a beam-like trace followed by a sudden jump in the energy loss in a specific strip due to the larger charge of the evaporation residue. Experimental fusion traces for the \(^{17}\)F + \(^{12}\)C system occurring in strip 7 are shown by the red lines in Fig. 2. Multiplicity information from the left and right sides of the detector are used to discriminate fusion-like events from scattering events.

\textit{Encore} provides full angular coverage of the evaporation residues allowing for a measurement of the total fusion cross section per strip. This translates into a measurement of the fusion excitation function of the system over a wide energy range using a single beam energy. The range of the excitation function is determined solely by the energy of the beam and the gas pressure in the detector. Since \textit{Encore} measures all the beam all the time, it provides an absolute beam normalization of the measured fusion cross sections. \textit{Encore} is particularly efficient for fusion measurements with low-intensity exotic beams \((\lesssim 10 \text{ kHz})\) since there is no need to re-tune
FIG. 1. Upper panel: 3D schematic of the *Encore* detector, a multi sampling ionization chamber where the field cage produces a perpendicular electric field. The field cage consists of a negatively biased cathode, voltage divider wired planes, a Frisch grid and a segmented anode. The beam passes through the center of the active region. Lower panel: Schematic view of the segmented anode. The first and last strips are used as veto and control, respectively. The 16 strips subdivided into left and right halves are also shown. The black arrow indicates a beam particle entering the active region of the detector. A fusion reaction occurs in strip 7 creating an evaporation residue (red arrow) which is identified by its larger energy loss signal.

FIG. 2. Experimental traces measured in *Encore*. The beam traces inside the detector (black) have been normalized to a fixed value for the analysis. The normalization allows a consistent threshold to be set when searching for energy jumps within the segmented anode strips of the detector. Experimental $^{17}$F + $^{12}$C fusion events occurring in strip 7 are shown by the red traces. A jump in energy loss is seen as a result of the creation of an evaporation residue which will stop in the detector prior to the beam. The inset in the top-left corner shows the separation of the $^{17}$F and $^{16}$O beams in *Encore* due to their different time-of-flight.

| $E_{c.m.}$ (MeV) | $\sigma$ (mb) |
|------------------|---------------|
| 19.4 ± 0.5       | 914 ± 88      |
| 18.4 ± 0.5       | 797 ± 89      |
| 17.4 ± 0.5       | 728 ± 85      |
| 16.3 ± 0.5       | 789 ± 91      |
| 15.2 ± 0.5       | 831 ± 94      |
| 14.0 ± 0.6       | 704 ± 89      |
| 12.8 ± 0.6       | 660 ± 86      |
| 11.6 ± 0.6       | 516 ± 81      |
| 10.3 ± 0.6       | 240 ± 55      |
| 8.9 ± 0.7        | 150 ± 47      |

TABLE I. Fusion cross sections for the $^{17}$F + $^{12}$C system measured in the present experiment as a function of center of mass energy.

In the present experiment the fusion excitation function of the $^{17}$F + $^{12}$C system was measured inside the active region of the detector over the range in center of mass energy corresponding to $E_{c.m.} = 19.4 - 9.0$ MeV, with an average energy of 1.2 MeV deposited in each strip. In order to extract a relative fusion cross section, the identified fusion events per strip were counted and normalized to the beam events in the detector. The corresponding energy and the target thickness per strip, determined by the gas pressure and the size of the strip, were calculated using LISE++ [29] and used to determine the absolute cross section. The error bars on the cross section measurements are dominated by statistics. Systematic uncertainties are due to target thickness (size of the anode strips, the pressure of the gas, variations in temperature). A conservative minimum of 10% y-error bars on the cross sections has been adopted to account for systematic uncertainties. The error bars in energy arise from the 1.5 cm thickness of the strips and the possibility of the reaction occurring anywhere within the width of a particular strip. The x-error bars consider that the reaction occurred in the middle of the strip concerned. The measured fusion cross section values are reported in Table I.

Fusion events from the primary $^{16}$O beam were measured simultaneously in *Encore* with those for $^{17}$F. The fusion cross sections for the $^{16}$O + $^{12}$C system thus obtained are plotted on Fig. 3, together with previous measurements from the literature [30–33]. The good agreement between the present $^{16}$O + $^{12}$C fusion data and the previous measurements gives confidence in the $^{17}$F + $^{12}$C fusion measurements.

In order to make a systematic comparison of any effects on the fusion cross section due to the exotic nature of $^{17}$F, we also performed a measurement with its stable
FIG. 3. Fusion cross sections for the $^{16}$O + $^{12}$C (blue diamonds) and $^{19}$F + $^{12}$C (red triangles) systems measured in the present experiment compared with previously published data for both systems showing the good agreement obtained.

counterpart $^{19}$F on a $^{12}$C target. A 65 MeV $^{19}$F beam at a rate of $\sim 1 \times 10^{4}$ pps was delivered to Encore which was filled with CH$_4$ gas at a pressure of 131 Torr. This pressure was chosen to scan a similar range in center of mass energy to the $^{17}$F + $^{12}$C measurement. The $^{19}$F arrived in the first control strip at 51 MeV, depositing between 0.75 MeV and 1.2 MeV in each strip, with an average of 0.9 MeV. The absolute cross sections for the $^{19}$F + $^{12}$C system in the energy range $E_{c.m.} = 17.8 - 11$ MeV measured in this experiment are plotted on Fig. 3 together with previously published data [31][36]. The good agreement between the Encore measurements and the previous data confirms the consistency of our analysis procedure.

IV. ANALYSIS

One of the big issues when comparing fusion data for different interacting systems and in particular when addressing whether cross sections are enhanced or hindered, is the various ways that fusion data from different systems are presented and compared. While various reduced units can be found in the literature [37][39], we present our results using the reduced units defined by Gomes et al. [40] which eliminate the so-called ‘geometrical effects’. In this representation:

$$E_{\text{red}} = E_{\text{c.m.}} \times (A_p^{1/3} + A_t^{1/3})/(Z_tZ_p)$$

(1)

and

$$\sigma_{\text{red}} = \sigma/(A_p^{1/3} + A_t^{1/3}),$$

(2)

where $E_{\text{c.m.}}$ is the energy in the center-of-mass system in MeV, $\sigma$ is the measured cross section in mb, and $A_p$, $A_t$, $Z_p$, and $Z_t$ refer to the mass $(A)$ and the nuclear charge $(Z)$ of the projectile $(p)$ and target $(t)$ nuclei involved in the reaction.

In employing these reduced units we seek to minimize biases arising from “trivial” differences in Coulomb barrier heights and the $A^{1/3}$ nuclear radius variation which could “wash out” any structure effects that may be evident in the data [40]. Using this convention, our measurements of the $^{17}$F + $^{12}$C fusion excitation function are plotted together with those for the $^{19}$F + $^{12}$C and $^{16}$O + $^{12}$C systems carried out under the same experimental conditions using the Encore detector at FSU in Figs. 4 and 5 respectively.

The data were analyzed using the code CCFULL [11] which uses a Woods-Saxon nuclear potential and takes into account incoming wave boundary conditions, assuming complete absorption inside the Coulomb barrier. Vibrational and rotational excitations of projectile and/or target may be included via the coupled channel method. However, it was found that no couplings were needed to reproduce the experimental results, which were well described by a barrier penetration calculation [12]. The extracted fusion barriers ($V_b$), fusion radii ($R_b$), and barrier curvatures ($\omega$) are given in Table II.

The measured fusion cross sections for the $^{17}$F + $^{12}$C (black circles) and $^{19}$F + $^{12}$C (red triangles) systems are plotted in reduced units in Fig. 3. Both data sets, when compared in reduced units, agree with each other well over the measured energy range. No enhancement of the $^{17}$F fusion cross section is observed. The calculations for both systems performed with CCFULL are also shown in Fig. 3 as solid and dotted lines for the $^{17}$F + $^{12}$C and $^{19}$F + $^{12}$C systems, respectively. No couplings to excited states of the target or projectile were needed to fit the data. The extracted barrier parameters for $^{17}$F were: $V_b = 8.83$ MeV, $R_b = 8.04$ fm and $\omega = 2.87$ MeV, in agreement with those obtained for $^{19}$F: $8.68$ MeV, $8.31$ fm, and $2.98$ MeV, respectively. These results suggest that the weak binding of $^{17}$F and the possible proton halo nature of its low-lying $1/2^+$ excited state have little or no influence on the fusion cross section in the measured energy range, confirming previous results for the heavy system $^{17}$F + $^{208}$Pb [9][22].

A comparison was also made between the fusion cross

| System | $V_b$ (MeV) | $R_b$ (fm) | $\omega$ (MeV) |
|--------|-------------|------------|----------------|
| $^{16}$O + $^{12}$C | 7.85 | 7.96 | 2.63 |
| $^{19}$F + $^{12}$C | 8.68 | 8.31 | 2.98 |
| $^{17}$F + $^{12}$C | 8.83 | 8.04 | 2.87 |

TABLE II. Fusion barrier parameters for the systems studied in this work extracted with the code CCFULL.
sections for the $^{17}$F + $^{12}$C (black circles) and $^{16}$O + $^{12}$C (blue diamonds) systems, see Fig. 5. No enhancement of the $^{17}$F fusion cross section compared to that for its $^{16}$O core is observed when the excitation functions are plotted in reduced units. The CCFULL calculations for these two systems are also shown in Fig. 5 as the solid and dotted lines, respectively. No couplings were included. The $V_b$ values extracted for $^{17}$F and $^{16}$O are different, 8.83 MeV and 8.22 MeV, respectively, as expected due to their differing $Z$ values. However, their reduced values, 0.795 and 0.792, respectively, are almost identical, suggesting that the valence proton has little or no influence on the $^{17}$F fusion cross section over the measured energy range. The $R_b$ values are also similar: 8.04 fm and 7.85 fm, respectively, again indicating that the valence proton has no influence on the fusion.

The lack of enhancement of the $^{17}$F fusion cross sections compared to those for its $^{16}$O core is consistent with calculated values of the ground state r.m.s. matter radius of $^{17}$F which yield values similar to that of the ground state of $^{16}$O (see, e.g., Ref. [43]). While the r.m.s. radius of the $^{17}$F 0.495 MeV 1/2+ excited state is significantly larger, commensurate with its proposed halo status, the lack of enhancement of the $^{17}$F fusion cross section strongly suggests that its influence on the fusion process is small, either through coupling effects on the fusion barrier height or directly as a result of fusion of the $^{17}$F after being excited to this state.

In order further to test this conclusion, coupled channel calculations were performed with the code FRESCO [44] which allows the use of externally calculated potentials. The real part of the nuclear potential was calculated using the double folding procedure with the M3Y nucleon-nucleon interaction [45]. The $^{17}$F nuclear matter density was taken from Ref. [46] and the $^{12}$C matter density was derived from the charge density of Ref. [47] by unfolding the proton charge density and assuming that $\rho_{nuc} = (1 + N/Z)\rho_p$. The double-folded potential was calculated with the code DFPT [48]. An imaginary potential of Woods-Saxon squared form with parameters $W = 50$ MeV, $r = 1.0 \times (12^{1/3} + 17^{1/3})$ fm, $a = 0.3$ fm effectively reproduced the ingoing-wave boundary condition, the fusion being calculated as the total absorption by this potential in all channels.

Couplings to the 0.495-MeV 1/2+ state of $^{17}$F and the 4.44-MeV 2+ state of $^{12}$C were included using standard collective model form factors. The $B(E2)$ for the $^{17}$F coupling was taken from Ref. [49] and the nuclear deformation length was derived from this value assuming the collective model and a radius of $1.3 \times 17^{1/3}$ fm. The $^{12}$C $B(E2)$ was taken from Ref. [50] and the nuclear deformation length from Ref. [51].

It is possible to calculate the absorption by the imaginary potential for individual channels using FRESCO, equivalent to the fusion cross section in the model used here. In Fig. 6 we present the excitation functions for the total fusion and for each of the following channels: the entrance channel with both the $^{17}$F projectile and the $^{12}$C target in their respective ground states, the $^{17}$F in its 0.495-MeV 1/2+ excited state and the $^{12}$C in its ground state, and the $^{17}$F in its ground state and the $^{12}$C in its 4.44-MeV 2+ excited state. Mutual excitation was not considered. The data are omitted for the sake of clarity, but they are well reproduced by the calculated complete fusion excitation function.

The fusion excitation function obtained from the no-coupling calculation (not shown) is visually indistinguishable from the coupled channel result on the scale of the figure, thus the coupling effects of both the 0.495-MeV 1/2+ $^{17}$F excited state and the 4.44-MeV 2+ $^{12}$C excited state on the fusion are negligible, confirming the conclusions of the CCFULL calculations. However, the break-

FIG. 4. Reduced fusion cross sections for the $^{17}$F + $^{12}$C (black circles) and $^{16}$O + $^{12}$C (red triangles) systems measured in this work. The corresponding CCFULL calculations with no coupling included are denoted by the solid and dotted lines, respectively. The fusion barriers extracted from the fits are indicated by the vertical arrows.

FIG. 5. Reduced fusion cross sections for the $^{17}$F + $^{12}$C (black circles) and $^{16}$O + $^{12}$C (blue diamonds) systems measured in this work. The corresponding CCFULL calculations with no coupling included are denoted by the solid and dotted lines, respectively. The fusion barriers extracted from the fits are indicated by the vertical arrows.
The fusion excitation function over a wide energy range can be measured with absolute normalization and without changing the beam energy. Systematic measurements with its stable counterparts $^{16}$O and $^{19}$F were also performed under the same experimental conditions. The analysis of the data and comparison in reduced units presented in this work indicate no special influence on the fusion cross section due to the specific structure of $^{17}$F, in particular the proton halo nature of its low-lying first excited state, confirming previous findings for the heavy-target $^{17}$F + $^{208}$Pb system [9]. The lack of a fusion enhancement in the present work with the low Z target nucleus $^{12}$C provides a test of the proposal by Xue-Ying et al. [23] that in the $^{17}$F + $^{208}$Pb system no enhancement in the fusion cross section was observed because the large Coulomb field of the $^{208}$Pb target polarizes the $^{17}$F such that the proton follows the $^{16}$O core in its interaction with the target. Coupled channel calculations confirmed that the influence of coupling to the $^{17}$F proton halo state on the fusion cross section was negligible, and furthermore indicated that fusion from the channel with $^{17}$F propagating in this state makes a negligible contribution to the total fusion. Thus, the halo nature of the 0.495-MeV $1/2^+$ excited state of $^{17}$F is seen to have little or no influence on the total fusion in the $E_{c.m.}$ range, thus explaining the similarity of the fusion cross sections for the $^{17}$F, $^{19}$F, and $^{16}$O + $^{12}$C systems when plotted in reduced units.

The self-normalizing and efficient capabilities of the Encore detector make it an ideal system systematically to study the fusion cross sections for other proposed proton-halo nuclei: $^8$B [17-18], $^{17}$Ne [52], and $^{27}$P [53] and thus determine whether there is any enhancement of the fusion cross section for these nuclei at energies above the Coulomb barrier. Other “detector targets” such as Ne, Ar, Kr and Xe could be used further to explore the Z dependence of the fusion cross sections for exotic proton-halo nuclei.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation under grants PHY-1712953 and PHY-2012522, and by the State of Florida.

V. CONCLUSIONS

In summary, an experimental campaign to study the influence of the structure of the weakly-bound, proton drip-line nucleus $^{17}$F on its fusion cross section with $^{12}$C was carried out using the Encore active-target detector system at FSU. Encore measures energy losses as the beam travels through the detector using a segmented an-
H. Fröhlich, P. Dücker, W. Galster, W. Treu, H. Voit, H. Witt, W. Kühl, and S.M. Lee. Oscillations in the excitation function for complete fusion of $^{18}$O+$^{12}$C at low energies. Phys. Lett. B, 64(4):408 – 410, 1976.

Y.-D. Chan, H. Bohn, R. Vandenbosch, K.G. Bernhardt, J.G. Cramer, R. Sielemann, and L. Green. Gross structure in $\gamma$-ray yields following the $^{16}$O+$^{12}$C reaction. Nucl. Phys. A, 303(3):500 – 520, 1978.

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.

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, 1976.

R. M. Anjos, V. Guimaraes, N. Added, N. Carlin Filho, M. M. Coimbra, L. Fante, M. C. S. Figueira, E. M. Szanto, C. F. Tenreiro, and A. Szanto de Toledo. Effect of the entrance channel mass asymmetry on the limitation of light heavy-ion fusion cross sections. Phys. Rev. C, 42:354–362, Jul 1990.

L. F. Canto, P R S Gomes, J. Lubian, L.C. Chamon, and E. Crema. Disentangling static and dynamic effects of low breakup threshold in fusion reactions. Journal of Physics G: Nuclear and Particle Physics, 36(1):015109, 2009.

L.F. Canto, P.R.S. Gomes, J. Lubian, L.C. Chamon, and E. Crema. Dynamic effects of breakup on fusion reactions of weakly bound nuclei. Nucl. Phys. A, 821(1):51 – 71, 2009.

J.M.B. Shorto, P.R.S. Gomes, J. Lubian, L.F. Canto, S. Mukherjee, and L.C. Chamon. Reaction functions for weakly bound systems. Phys. Lett. B, 678(1):77 – 81, 2009.

P. R. S. Gomes, J. Lubian, I. Padron, and R. M. Anjos. Uncertainties in the comparison of fusion and reaction cross sections of different systems involving weakly bound nuclei. Phys. Rev. C, 71:017601, 2005.

K. Hagino, N. Rowley, and A.T. Kruppa. A program for coupled-channel calculations with all order couplings for heavy-ion fusion reactions. Computer Physics Communications, 123(1):143 – 152, 1999.

C. Y. Wong. Interaction barrier in charged-particle nuclear reactions. Phys. Rev. Lett., 31:766–769, 1973.

Zhang Hu-Yong, Shen Wen-Qing, Ren Zhong-Zhou, Ma Yu-Gang, Chen Jin-Gen, Cai Xiang-Zhou, Lu Zhao-Hui, Zhong Chen, Guo Wei, Wei Yi-Bin, Zhou Xing-Fei, Ma Guo-Liang, and Wang Kun. Structures of 17f and 17o, 17 ne and 17 n in the ground state and the first excited state. Chinese Physics Letters, 20(9):1462–1465, aug 2003.

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

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

R. Capote, M. Herman, P. OhloÀinskÅ~A, P.G. Young, S. Goriely, T. Belgya, A.V. Ignatyuk, A.J. Koning, S. Hilaire, V.A. Plujko, M. Avrigeanu, O. Bersillon, M.B. Chadwick, T. Fukushima, Zhigang Ge, Yinlu Han, S. Kailas, J. Kopecky, V.M. Maslov, G. Reffo, M. Sin, E.Sh. Soukhovitskii, and P. Talou. Ripl â€“ reference input parameter library for calculation of nuclear reactions and nuclear data evaluations. Nuclear Data Sheets, 2009.
[47] 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.

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

[49] C.A. Bertulani, G. Cardella, M. De Napoli, G. Raciti, and E. Rapisarda. Coulomb excitation of unstable nuclei at intermediate energies. *Physics Letters B*, 650(4):233 – 238, 2007.

[50] 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.

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

[52] K. Tanaka, M. Fukuda, M. Mihara, M. Takechi, D. Nishimura, T. Chinda, T. Sumikama, S. Kudo, K. Matsuta, T. Minamisono, T. Suzuki, T. Ohtsubo, T. Izumikawa, S. Momota, T. Yamaguchi, T. Onishi, A. Ozawa, I. Tanihata, and T. Zheng. Density distribution of $^{17}$Ne and possible shell-structure change in the proton-rich $sd$-shell nuclei. *Phys. Rev. C*, 82:044309, 2010.

[53] D.Q. Fang, W.Q. Shen, J. Feng, X.Z. Cai, H.Y. Zhang, Y.G. Ma, C. Zhong, Z.Y. Zhu, W.Z. Jiang, W.L. Zhan, Z.Y. Guo, G.Q. Xiao, J.S. Wang, J.Q. Wang, J.X. Li, M. Wang, J.F. Wang, Z.J. Ning, Q.J. Wang, and Z.Q. Chen. Evidence for a proton halo in $^{27}$P through measurements of reaction cross-sections at intermediate energies. *Eur. Phys. J. A*, 12(3):335–339, 2001.