PHYSICAL REVIEW C **89**, 024306 (2014)

^{16}O resonances near the 4α threshold through the ^{12}C(^{6}Li,d) reaction

M. R. D. Rodrigues,[1,*] T. Borello-Lewin,[1] H. Miyake,[1] J. L. M. Duarte,[1] C. L. Rodrigues,[1] M. A. Souza,[1] L. B. Horodynski-Matsushigue,[1] G. M. Ukita,[2] F. Cappuzzello,[3,4] A. Cunsolo,[4] M. Cavallaro,[4] C. Agodi,[4] and A. Foti[3,5]

[1]*Instituto de Física, Universidade de São Paulo, Caixa Postal 66318, CEP 05314-970, São Paulo, SP, Brazil*

[2]*Faculdade de Psicologia, Universidade de Santo Amaro, R. Prof. Eneas da Siqueira Neto, 340, CEP 04829-300, São Paulo, SP, Brazil*

[3]*Università di Catania, Dipartimento di Fisica e Astronomia, Via S. Sofia 64, 95123 Catania, Italy*

[4]*INFN–Laboratori Nazionali del Sud, Via S. Sofia 62, 95125 Catania, Italy*

[5]*INFN–Sezione di Catania, Via S. Sofia 64, 95125 Catania, Italy*

(Received 16 September 2013; revised manuscript received 2 December 2013; published 11 February 2014)

Background: Resonances around $x\alpha$ thresholds in light nuclei are recognized to be important in basic aspects of nuclear structure. However, there is scarce experimental information associated with them.

Purpose: We study the α-clustering phenomenon in resonant states around the 4α threshold (14.44 MeV) in the ^{16}O nucleus.

Method: The ^{12}C(^{6}Li,d)^{16}O reaction was investigated with an unprecedented resolution at a bombarding energy of 25.5 MeV by employing the São Paulo Pelletron-Enge-Spectrograph facility and the nuclear emulsion technique.

Results: Several narrow resonances were populated and the energy resolution of 15 keV allows for the separation of doublet states that were not resolved previously. The upper limits for the resonance widths in this region were extracted. The angular distributions of the absolute differential cross section associated with four natural parity quasibound states are presented and compared to distorted wave Born approximation predictions.

Conclusions: Narrow resonances not previously reported in the literature were observed. This indicates that the α-cluster structure information in this region should be revised.

DOI: 10.1103/PhysRevC.89.024306 PACS number(s): 25.40.Hs, 21.60.Gx, 21.10.Tg

I. INTRODUCTION

The α-clustering phenomenon in the structure of light nuclei has been the subject of a longtime investigation since the proposal of Ikeda diagrams [1]. However, the mechanism of cluster formation is still not completely understood. In fact, whether the cluster configuration has a fairly rigid crystal-like or a gas-like structure remains an open question [2–9]. An investigation of this phenomenon in $x\alpha$ and $x\alpha + n$ nuclei through (^{6}Li,d) transfer reactions has been performed in São Paulo [10–15]. Particularly interesting are the regions around the $x\alpha$ thresholds that are recognized to be important in the production of the elements in stars, as primarily pointed out by Hoyle in ^{12}C [1,16]. The interpretation of the Hoyle state as an α condensate brought renewed interest to this subject [7]. Recently, a rotational band with the α + ^{12}C (Hoyle) cluster state structure was predicted by Ohkubo and Hirabayashi [6] near the 4α threshold (14.44 MeV). The resonant states in the ^{16}O nucleus around the 4α threshold are the focus of the present work. For this purpose the ^{12}C(^{6}Li,d)^{16}O reaction was experimentally investigated with an unprecedented resolution of 15 keV at a bombarding energy of 25.5 MeV.

II. EXPERIMENTAL PROCEDURE

A 25.5-MeV ^{6}Li beam from the São Paulo Pelletron Accelerator was focused on a uniform target of natural C. Two targets of 110 and 30 μg/cm^2 thicknesses were used. The deuterons emerging from the (^{6}Li,d) reaction were momentum analyzed by the magnetic field of the Enge-Spectrograph and detected on emulsion plates (Fuji G6B, 50 μm thick). The acceptance solid angles of the spectrograph, for the respective thick and thin targets, were $\Delta\Omega = 0.268(3)$ and 1.237(4) msr, resulting in angular full widths of $\Delta\theta_H = 0.38^\circ$ and 1.75°.

Spectra associated with nine scattering angles between 5° and 32° in the laboratory frame, each one along 50 cm of the focal plane, were measured from 13.5 to 15.5 MeV excitation energy. After processing, the plates were scanned in strips of 200 μm along the dispersive direction with an optical microscope. The spectra were obtained by plotting the number of tracks per strip versus the position along the focal plane (L). Figure 1 displays the region around the 4α threshold in the measured deuteron position spectra at different scattering angles obtained with the thinner target. An identification label is indicated for each transition and the respective excitation energies are listed in Table I.

Energy calibration was obtained through fitting a second-order polynomial with the ion trajectory radii (ρ) calculated for the well-known ^{16}O excited energies of 13.980, 14.302, 14.399, 14.815, and 14.926 MeV [17] as a function of L for the respective peaks. The estimated accuracy in the energy determination is about 10 keV. Excellent energy resolutions of 30 and 15 keV were achieved for thick and thin targets, respectively, mainly due to their high uniformity and the careful choice of the nuclear plate position at the focal plane. The energy resolution was determined through the the full width at half maximum (FWHM) of the peaks corresponding to several bound states of ^{16}O. Three spectra up to 10.5 MeV excitation energy were measured. Figure 2 shows, as an example, the deuterium position spectrum at $\theta_{\rm lab} = 11^\circ$.

The relative normalization of each spectrum was referred to the total beam charge collected in each run. The absolute scale

*marciadr@if.usp.br

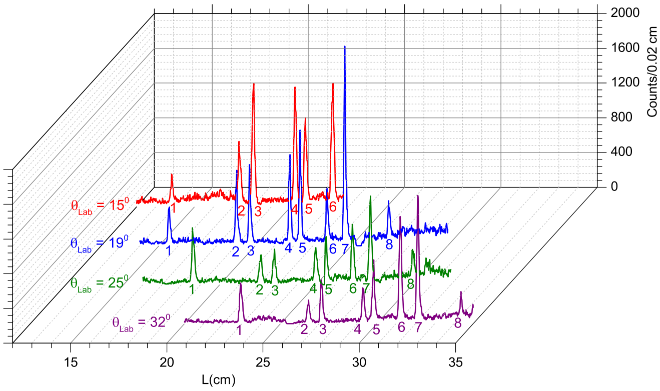

FIG. 1. (Color online) Deuteron position spectra for $\theta_{\text{lab}} = 15^\circ$, 19°, 25°, and 32° near the 4α threshold. Peaks referring to the same transition are labeled by the same number.

of the cross sections was determined by comparison of optical model predictions for elastic scattering with measurements on the same target under similar conditions. An overall accuracy of 20% is estimated for the absolute cross sections.

III. ANALYSIS

The energy and the line width for the resonant states were obtained by the position and the FWHM through the fit of the peaks using a χ^2 minimization procedure. The function applied was a combination of two Gaussian functions for each peak shape and a linear function for the background contribution (see the example in Fig. 3). This description accounts for the slight asymmetric response function of the spectrograph.

Table I presents, for each level, the mean excitation energy E_{level} and the FWHM obtained from the thinner target spectra. The respective statistical uncertainties listed are the standard deviation of the set of energy and FWHM obtained. The excitation energies reported in [17,18] and the J^π values attributed in [17] are also shown.

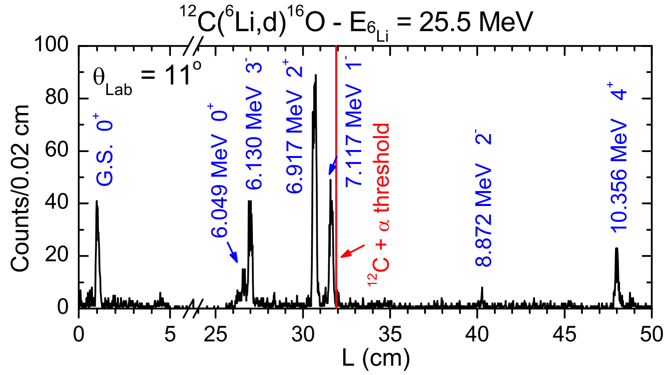

FIG. 2. (Color online) Deuteron position spectra for $\theta_{\text{lab}} = 11^\circ$. The energy level and the J^π values presented are from Tilley *et al.* [17].

The angular distributions of the absolute differential cross section, not previously reported, associated with the resonances of natural parity at 14.614, 14.670, 14.825, and 14.931 MeV excitation energy, are presented in Fig. 4. Note that the angular distributions include the data taken with both targets. The cross-section uncertainties take into account the statistical, the scanning, and the background-subtraction contributions.

One-step α transfer finite-range distorted wave Born approximation (DWBA) calculations were performed using the code DWUCK5 [19] for the natural parity states. In order to obtain more information on the entrance channel optical model parameters, measurements of the ^{6}Li elastic scattering on ^{12}C at 25.5 MeV were performed. The corresponding angular distribution is shown in Fig. 5. The parameters search started from the optical model potential set of Cook [20], obtained in a global analysis covering the energy range from 13 to 156 MeV and a target mass range of 24–208. The results are shown in Fig. 5, where the experimental elastic angular distribution is compared with optical model calculations using the Cook [20]

TABLE I. Energy levels and FWHM line widths obtained in the present work in comparison with the results reported in the literature.

Transition	E_{level} [a] (keV)	FWHM[a] (keV)	E_{level} [b] (keV)	FWHM[b] (keV)	E_{level} [c] (keV)	$\Gamma^{c}_{c.m.}$ (keV)	$J^{\pi c}$
1	13988(2)	<13(3)	13983(2)	70(6)	13980(2)	20(2)	2^-
2	14316(6)	<15(3)	14297(3)	66(7)	14302(3)	34(12)	$4^{(-)}$
3	14392(6)	<16(3)	14396(2)	64(5)	14399(2)	27(5)	5^+
					14620(20)	490(15)	$4^{(+)}$
4	14614(2)	<15(2)					
			14566(11)	450(27)	14660(20)	670(15)	5^-
5	14670(3)	<15(3)					
6	14825(3)	<18(3)	14808(3)	93(6)	14815.3(16)	70(8)	6^+
7	14931(2)	<18(2)	14911(20)	103(30)	14926(2)	54(5)	2^+
8	15198(2)	<18(3)			15196(3)	63(4)	2^-

[a]Present work. The uncertainties listed are statistical. The E_{level} values have an accuracy of 10 keV. The observed line width (FWHM) is considered as an upper limit for Γ_α (see text).
[b]Wheldon *et al.* [18].
[c]Tilley *et al.* [17].

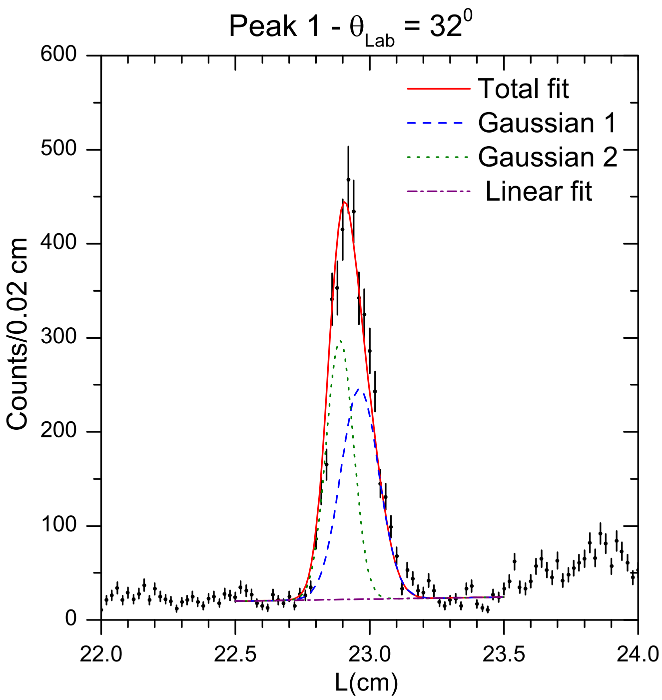

FIG. 3. (Color online) Partial spectrum showing the fit of a typical peak in the spectrum with two Gaussian functions and a linear function for background subtraction.

parameters and slightly modified geometrical parameters of $r_R = 1.25$ fm and $a_R = 0.65$ fm.

The DWBA calculations employ the modified set of parameters based on Cook [20] for the entrance channel and global optical model parameters from Daehnick *et al.* [21] for the exit channel. The binding potential of Kubo and Hirata [22] was taken for the $\alpha + d$ description of ^{6}Li. Although resonant, the α states under consideration were assumed to be bound by 100 keV in a Woods-Saxon binding potential with reduced radius of 1.25 fm and diffusivity of 0.65 fm. Relative to the ^{12}C core, the global quantum number G [23] values 8 and 9 were considered, respectively, for positive- and negative-parity α states.

IV. RESULTS

The DWBA calculations are presented in comparison with the experimental data in Fig. 4. This DWBA analysis shows important direct contributions associated with the resonant states at 14.614, 14.670, and 14.931 MeV. These states are reached by $L = 4$, 5, and 2 transitions, respectively, pointing to $J^\pi = 4^+$, 5^-, and 2^+. On the other hand, for the state at 14.825 MeV the shape of the experimental angular distribution could not be reproduced by using the present approach. For a better illustration, the $L = 0,2$, 4, and 6 DWBA predictions are shown. A $J^\pi = 6^+$ assignment is indicated by Tilley *et al.* [17].

In the region of the 0^+ state at 15.1 MeV, where the gas-like configuration of the 4α condensate state is expected [2], only one state is observed in the present work. This is most likely the state $J^\pi = 2^-$ at 15.196 MeV, as also indicated in Ref. [18].

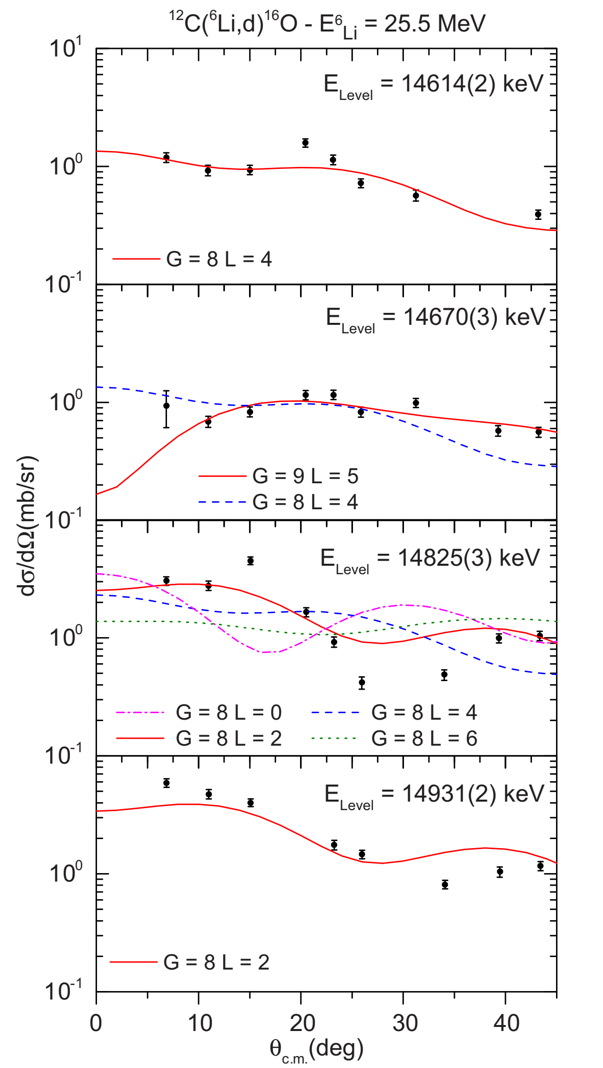

FIG. 4. (Color online) Experimental angular distributions for natural parity states and their respective DWBA predictions.

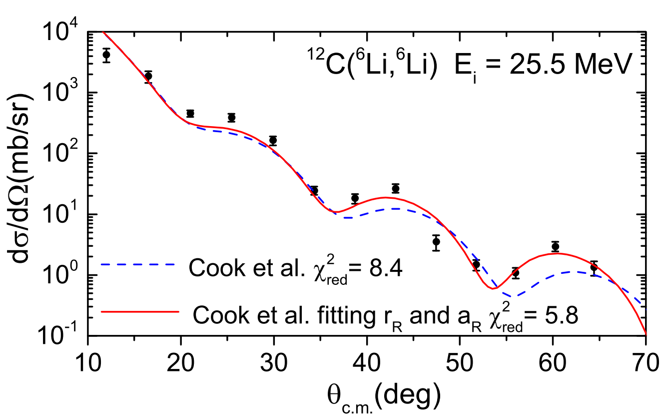

FIG. 5. (Color online) Experimental angular distribution for the elastic scattering of ^{6}Li on ^{12}C in comparison with DWBA predictions using the Cook [20] parameters and a modified set of parameters based on Cook ($r_R = 1.25$ fm and $a_R = 0.65$ fm).

In the present reaction the condensate state is expected to be at most very weakly excited, since it requires the excitation of the Hoyle state followed by the α transfer. In comparison to the $^{12}C(2_1^+)$ shape vibration, the inelastic excitation of the Hoyle state is very unlikely due to the different configuration of this state.

The α width Γ_α and line width $\Gamma_{c.m.}$ can be considered equivalent in the context of the one-level approximation [24]. In fact, $\Gamma_\alpha = \Gamma_{c.m.}$ has been considered often in the literature [25]. In the present work we assume $\Gamma_{c.m.}$ as an upper limit for the resonance widths Γ_α. The FWHM from Wheldon *et al.* [18] and the $\Gamma_{c.m.}$ from Tilley *et al.* [17] are presented in Table I in comparison with the FWHM extracted in the present work. Our upper limits for the resonance widths are practically equal to the experimental energy resolution. It is interesting to note that the 5^+ state at 14.392 MeV could be considered as a candidate member of the $^{12}C(2_1^+) + \alpha$ band, by taking into account both the excitation energy and width.

The energy resolutions of the former (^{6}Li,d) works [18,26–29] are in the range of 60–160 keV. The work of Wheldon *et al.* [18] is the most recent and with the best energy resolution (60 keV). The $^{12}C(^6Li,d)$ reaction was measured at an incident energy of 42 MeV in coincidence with α decay of ^{16}O to ^{12}C(g.s.) and $^{12}C(2_1^+)$. Three states of unnatural parities at 13.983, 14.297, and 14.396 MeV with consistent predominant decaying branches to the $^{12}C(2_1^+)$ state were reported. These three states were also observed in the present work. Note that the FWHM obtained by Wheldon *et al.* [18] for these three resonances (see Table I) are of the same order as their energy resolution. One state at 14.566 MeV associated with a strongly populated broad resonance which decays to the ^{12}C(g.s.) and a highly excited state at 14.808 MeV decaying to both ^{12}C(g.s.) and $^{12}C(2_1^+)$ were reported. The fact that the latter state has an important decay component to the 2_1^+ state can explain the poor agreement of the experimental angular distribution with the DWBA predictions in the present work. The resonance at 14.911 MeV is weakly populated and was not well resolved by Wheldon *et al.* [18], but it is clearly defined in this work.

It is important to point out that the doublet at 14.614 and 14.670 MeV is completely resolved in the present work with an upper limit of 15 keV for $\Gamma_{c.m.}$. The corresponding angular distributions indicate $J^\pi = 4^+$ and 5^- for those levels. In this region two broad resonances at 14.620(20) and 14.660(20) MeV are reported in the literature [17], with $\Gamma_{c.m.} = 490(15)$ and 670(15) keV respectively, associated with $J^\pi = 4^{(+)}$ and 5^-.

Measurements of d-α correlation functions for $^{12}C(^6Li,d) \rightarrow \alpha + {}^{12}C$ were presented by Cunsolo *et al.* [27] and Artemov *et al.* [29]. Cunsolo *et al.* obtained, with an energy resolution of 100 keV, $J^\pi = 5^-$ for the resonance at 14.5 MeV decaying to ^{12}C(g.s.). Artemov *et al.* measured the same resonance, with an energy resolution of 120 keV, reporting 94(10)% decaying to ^{12}C(g.s.) and less than 5% to $^{12}C(2_1^+)$. The $J^\pi = 4^{(+)}$ level was not reported by Wheldon *et al.*, Cunsolo *et al.*, or Artemov *et al.* On the other hand, these two broad resonances were reported in phase-shift analyses of α scattering measurements [30–33].

The broad 5^- resonance was interpreted theoretically and experimentally in the literature [3,4,17,33] as a member of the $K^\pi = 0^-$ $^{12}C(g.s.) + \alpha$ band. The predicted [4,6] and experimental [17] α widths, Γ_α, for the resonance states of this α band are in the range of 700–1800 keV and 400–900 keV, respectively. It is to be noted, however, that, in the same excitation energy range, a narrow 5^- resonance decaying to $^{12}C(2_1^+)$ was predicted by Suzuki [4], using a comprehensive semimicroscopic α-cluster calculation. In fact, the relative α-core energy, according to this description, is smaller than that in the $^{12}C(g.s.) + \alpha$ system. Consequently a longer lifetime or a quasibound behavior in the continuum is expected, in contrast with that of the broad resonance associated with the $^{12}C(g.s.) + \alpha$ structure. In the present data, a clear indication of the population of the narrow 5^- resonance is achieved. One should also mention that Haigh *et al.* [34], in the investigation of the ^{12}C decay products of the ^{16}O 5^- resonance, detected not only a ^{12}C(g.s.) but also a small $^{12}C(2_1^+)$ contribution. On the other hand, the energy resolution in that work [34] did not resolve the resonances in this region. A direct transfer to the narrow 5^- resonance would imply a sizable configuration mixing between $^{12}C(g.s.) + \alpha$ and $^{12}C(2_1^+) + \alpha$ components in the wave function. However, a pure $^{12}C(2_1^+) + \alpha$ configuration cannot be excluded given that two-step processes could populate it.

In this context, there are indications that the two narrow resonances observed at 14.614 and 14.670 MeV are associated with the $^{12}C(2_1^+) + \alpha$ component in the wave functions. Furthermore, it is possible that the two broad resonances reported in the literature are present in the data, although for a firm statement better statistics would be needed. In fact, a broad bump was revealed after aligning the peaks associated with the same state to compensate for kinematic recoil differences, discounting the identified contribution for the respective peaks, and summing all spectra taken with the same target.

V. CONCLUSIONS

The $^{12}C(^6Li,d)^{16}O$ reaction, measured at a beam energy of 25.5 MeV, populated eight narrow resonances in ^{16}O from excitation energies of 13.5–15.5 MeV. Around the 4α threshold, the excellent energy resolution of the data allows the separation of three doublets not previously resolved in α transfer reactions. The experimental angular distributions associated with natural parity states are reported for the first time. The shape is reproduced by DWBA calculations, demonstrating the importance of the direct process in the transitions to three of these resonances. The upper limit of the widths obtained are practically equal to the experimental energy resolution. The narrow widths for the 4^+ and 5^- resonances at 14.614 and 14.670 MeV are reported here for the first time, indicating that the α-cluster structure information in this region should be revised.

ACKNOWLEDGMENTS

This work was partially supported by the Brazilian funding agencies FAPESP and CAPES.

[1] K. Ikeda, N. Takigawa, and H. Horiuchi, Prog. Theor. Phys. Suppl. E **68**, 464 (1968).
[2] Y. Funaki, T. Yamada, A. Tohsaki, H. Horiuchi, G. Röpke, and P. Schuck, Phys. Rev. C **82**, 024312 (2010).
[3] Y. Suzuki, Prog. Theor. Phys. **55**, 1751 (1976).
[4] Y. Suzuki, Prog. Theor. Phys. **56**, 111 (1976).
[5] N. Furutachi, M. Kimura, A. Doté, Y. Kanada-En'yo, and S. Oryu, Prog. Theor. Phys. **119**, 403 (2008).
[6] S. Ohkubo and Y. Hirabayashi, Phys. Lett. B **684**, 127 (2010).
[7] M. Itoh *et al.*, Phys. Rev. C **84**, 054308 (2011).
[8] T. Yamada, Y. Funaki, T. Myo, H. Horiuchi, K. Ikeda, G. Röpke, P. Schuck, and A. Tohsaki, Phys. Rev. C **85**, 034315 (2012).
[9] J. P. Ebran, E. Khan, T. Niksic, and D. Vretenar, Nature (London) **487**, 341 (2012).
[10] M. R. D. Rodrigues, T. Borello-Lewin, L. B. Horodynski-Matsushigue, A. Cunsolo, F. Cappuzzello, J. L. M. Duarte, C. L. Rodrigues, G. M. Ukita, M. Cavallaro, and S. E. A. Orrigo, in *XXX Nuclear Physics Meeting in Brazil, Águas de Lindóia, SP, Brazil*, edited by Alexandre A. P. Suaide (XXX RTFNB Proceedings, Sao Paulo, 2007) p. 40.
[11] M. R. D. Rodrigues, T. Borello-Lewin, L. B. Horodynski-Matsushigue, A. Cunsolo, F. Cappuzzello, J. L. M. Duarte, C. L. Rodrigues, G. M. Ukita, M. A. Souza, and H. Miyake, in *12th International Conference on Nuclear Reaction Mechanism, Varenna, Italy*, Vol. 2, edited by F. Cerutti and A. Ferrari (CERN Proceedings, Geneva, 2010), p. 331.
[12] M. R. D. Rodrigues, T. Borello-Lewin, L. B. Horodynski-Matsushigue, A. Cunsolo, F. Cappuzzello, J. L. M. Duarte, C. L. Rodrigues, G. M. Ukita, M. A. Souza, and H. Miyake, AIP Conf. Proc. **1245**, 141 (2010).
[13] M. R. D. Rodrigues, T. Borello-Lewin, L. B. Horodynski-Matsushigue, A. Cunsolo, F. Cappuzzello, J. L. M. Duarte, C. L. Rodrigues, G. M. Ukita, M. A. Souza, and H. Miyake, AIP Conf. Proc. **1351**, 125 (2011).
[14] T. Borello-Lewin, L. Horodynski-Matsushigue, J. Duarte, C. Rodrigues, M. Souza, H. Miyake, M. Rodrigues, A. Cunsolo, F. Cappuzzello, and G. Ukita, Int. J. Mod. Phys. E **20**, 1018 (2011).
[15] T. Borello-Lewin, in *13th International Conference on Nuclear Reaction Mechanism, Varenna, Italy*, Vol. 2, edited by F. Cerutti and A. Ferrari (CERN Proceedings, Geneva, 2012) p. 195.
[16] F. Hoyle, D. N. F. Dunbar, W. A. Wenzel, and W. Whaling, Phys. Rev. **92**, 1095c (1953).
[17] D. Tilley, H. Weller, and C. Cheves, Nucl. Phys. A **564**, 1 (1993).
[18] C. Wheldon *et al.*, Phys. Rev. C **83**, 064324 (2011).
[19] P. D. Kunz, DWUCK5, http://spot.colorado.edu/~kunz/DWBA.html.
[20] J. Cook, Nucl. Phys. A **388**, 153 (1982).
[21] W. W. Daehnick, J. D. Childs, and Z. Vrcelj, Phys. Rev. C **21**, 2253 (1980).
[22] K.-I. Kubo and M. Hirata, Nucl. Phys. A **187**, 186 (1972).
[23] K. Wildermuth and Y. C. Tang, *A Unified Theory of the Nucleus* (Academic, New York, 1977).
[24] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. **30**, 257 (1958).
[25] F. Becchetti, E. Flynn, D. Hanson, and J. Sunier, Nucl. Phys. A **305**, 293 (1978).
[26] A. Cunsolo, A. Foti, G. Pappalardo, G. Raciti, and N. Saunier, Phys. Rev. C **18**, 856 (1978).
[27] A. Cunsolo, A. Foti, G. Immè, G. Pappalardo, G. Raciti, and N. Saunier, Phys. Rev. C **21**, 2345 (1980).
[28] F. Becchetti, J. Jnecke, and C. Thorn, Nucl. Phys. A **305**, 313 (1978).
[29] K. Artemov, V. Goldberg, I. Petrov, V. Rudakov, I. Serikov, and V. Timofeev, Phys. Lett. B **37**, 61 (1971).
[30] E. B. Carter, G. E. Mitchell, and R. H. Davis, Phys. Rev. **133**, B1421 (1964).
[31] T. Marvin and P. Singh, Nucl. Phys. A **180**, 282 (1972).
[32] P. Martin and T. Ophel, Nucl. Phys. A **202**, 257 (1973).
[33] L. L. Ames, Phys. Rev. C **25**, 729 (1982).
[34] P. J. Haigh *et al.*, J. Phys. G: Nucl. Part. Phys. **37**, 035103 (2010).