Study of Some $C^{12}(He^3,\alpha)C^{11}$ Reactions at 13.9 MeV*†

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The 13.9-MeV angular distributions for the $C^{12}(He^3,\alpha)C^{11}$ reactions which produce the ground, 2.00-, 4.32-, and 4.81-MeV states of C^{11} were measured, using silicon surface-barrier detectors. The differential cross sections were determined at 2.5° intervals over a laboratory angular range from about 15° to 100°. The angular distributions display features which suggest that a direct-reaction mechanism is operative. The ground-state angular distribution is strongly peaked at forward angles with a weak washed-out oscillatory structure, and those for the excited states are also forward-peaked, but have a strong, well-defined oscillatory nature. The integrated cross sections over the common center-of-mass angular range (32° to 112°) for the ground and first three excited states are 30.5, 9.2, 9.7, and 11.9 mb, respectively. Each angular distribution was analyzed in terms of both zero-range distorted-wave Born-approximation knockout and pickup models. Reasonable correspondence between theory and experiment for the ground-state ($\frac{3}{2}^-$) and second-excited-state ($\frac{5}{2}^-$) angular distributions was achieved only with the pickup model, while only the knockout model provided a reasonable representation of the angular distributions corresponding to the first ($\frac{1}{2}^-$) and third ($\frac{3}{2}^-$) excited states.

I. INTRODUCTION

ALTHOUGH there have been studies involving the measurement of angular distributions of $C^{12}(He^3,\alpha)C^{11}$ reactions at the initiating energies 1.8 to 5.4 MeV,[1] 2.0 to 6.2 MeV,[2] 6 to 10 MeV,[3] 8.5 to 10.0 MeV,[4] 16 to 18 MeV,[5,6] 21 MeV,[7] 24.8 MeV,[8] 28.5 MeV,[9] and 26 to 33 MeV,[10] with the exception of the work of Wegner and Hall[7] and that recently reported by Gray *et al.*[5,6] they have been concerned with the reaction(s) leading to the ground state[4,10] or to the ground and first excited states of C^{11}.[1–3,9] The only distorted-wave Born-approximation (DWBA) analyses which have been *fully* reported to date are the pickup analyses of the 8.5-, 9.0-, 10.0-MeV $C^{12}(He^3,\alpha_0)C^{11}$ angular distributions by Schwartz *et al.*,[4] and that by Hahn,[8] in which the 24.8-MeV composite angular distribution of the recoiling C^{11} nuclei for the various $C^{12}(He^3,\alpha)C^{11}$ reactions was analyzed. In both of these studies, a satisfactory DWBA description was achieved. The applicability of any of the DWBA formalisms presupposes that the operative reaction mechanism is one of the direct type. Unfortunately, for these reactions, the relative importance of the compound-nucleus (CN) and direct-reaction (DR) mechanisms as a function of energy has not been fully clarified experimentally. While the studies at lower incident energies, 1 to 5 MeV, indicate that the CN mechanism is responsible for the reactions,[1,2] the situation in the 6–10-MeV region is not well defined, since the data qualitatively suggest that both mechanisms may be operative.[3,4] For incident He^3 energies greater than about 16 MeV, the experimental data have been interpreted as indicating the dominance of the DR mechanism.[6,8,10]

It has also been observed for incident He^3 energies below about 10 MeV that the $C^{12}(He^3,\alpha)C^{11}$ reactions have large cross sections as compared with those for other nonelastic He^3-initiated channels.[1–3,11–14] As emphasized by Blake *et al.*,[2] such a circumstance would not be surprising if the reactions were of the direct type, since the (He^3,α) reaction is presumably a simpler process than those which produce other types of particles in the final state, i.e., n, p, or t. Moreover, these investigators suggest that if the CN mechanism were the operative process, and if the excited states of O^{15} have cluster structures derived largely from Be^7+Be^8 and He^3+C^{12} clusters, then, because of the α-particle substructure of Be^8 and C^{12}, it would not be unexpected if the emission of α particles was favored. Note that, in the absence of large CN-DR interference effects, the large relative strength of the (He^3,α) reactions in the

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[1] Hsin-Min Kuan, T. W. Bonner, and J. R. Risser, Nucl. Phys. **51**, 481 (1964).
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[9] J. Aguilar, W. E. Burcham, F. R. S., J. B. A. England, A. García, P. E. Hodgson, P. V. March, J. S. C. McKee, E. M. Mosinger, and W. T. Toner, Proc. Roy. Soc. (London) **A257**, 13 (1960).
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[11] D. A. Bromley, E. Almqvist, H. E. Gove, A. E. Litherland, E. B. Paul, and A. J. Ferguson, Phys. Rev. **105**, 957 (1957).
[12] S. D. Cirilov, J. O. Newton, and J. P. Shapiro, Nucl. Phys. **77**, 472 (1966).
[13] R. L. Hahn and E. Ricci, Phys. Rev. **146**, 650 (1966).
[14] D. F. R. Cochran and J. D. Knight, Phys. Rev. **128**, 1281 (1962).

energy regions where both the CN and DR are non-negligible contributors would be accounted for by the above proposals.

The experimental results show that, at initiating energies of 10 MeV and below, the cross sections for the production of the various excited states of C^{11} through the (He^3,α) reaction is from about 10 to 20% of that for producing the C^{11} ground state.[1-8] If one assumes that the C^{12} ground state is represented by the simple shell-model configuration $(1s)^4(1p_{3/2})^8$, then a simple pickup reaction could not produce the excited states. On the other hand, if it is assumed that the simple pickup mechanism is the interaction responsible for the transitions, then the experimental results must be interpreted as indicating that the description of the C^{12} ground state requires a configuration mixture. This latter conclusion is not inconsistent with what is known about the C^{12} ground state, and it would be reasonable to expect that a simple pickup model should predict the general features of the angular distributions associated with the excited states for those initiating energies at which the DR mechanism is dominant. In this connection, the adequacy of the simple DWBA pickup model has not been demonstrated.

Recognizing that the existence of a strong α-cluster character for the C^{12} ground state could favor a knockout mechanism in the $C^{12}(He^3,\alpha)C^{11}$ reactions, the present study was undertaken to measure the 13.9-MeV α-particle angular distributions associated with the low-lying states of C^{11} and to perform a DWBA knockout-model analysis of the experimental results. The completion of this study was subsequently found to require the execution of a complete DWBA pickup-model analysis. The details concerning the procedures and results of these measurements and analyses are presented in the following report.

II. EXPERIMENTAL

The measurements were made at the Purdue University 37-in. cyclotron facility, which has been described in some detail elsewhere.[15] He^3 particles were delivered to the target area with a mean energy of 13.950 MeV and an estimated rms spread of 40 keV. In the production of the He^3 beam, a gas recovery system was used which was similar to that developed by Wegner and Hall.[16]

The spectrometer system consisted of a four-counter particle-detector assembly; pulse-processing, logic, and routing electronics;[17] and a two-dimensional multichannel pulse-height analyzer.[18] The detector assembly was a rigidly mounted array of four individual counter assemblies, each containing a silicon surface-barrier counter[19] and a collimator system. It was constructed such that the target could be viewed at four different laboratory angles separated by 10° intervals and the entire detector assembly could be rotated about the target center through the azimuthal angular interval from 7° to 173°. The experimental geometry was such that the circular defining aperture of each counter subtended a solid angle of 0.664×10^{-3} sr and an azimuthal angle of 1.7° with respect to the target center. A functional block diagram of the spectrometer system is presented in Fig. 1.

A single carbon-foil target[20] was used throughout the course of theexper iment. The measured areal density of the target was 220 ± 11 $\mu g/cm^2$. The target was oriented at an angle of 45° to the beam. The reaction-particle spectrum was continuously monitored, using a fifth counter assembly positioned at 90° with respect to the

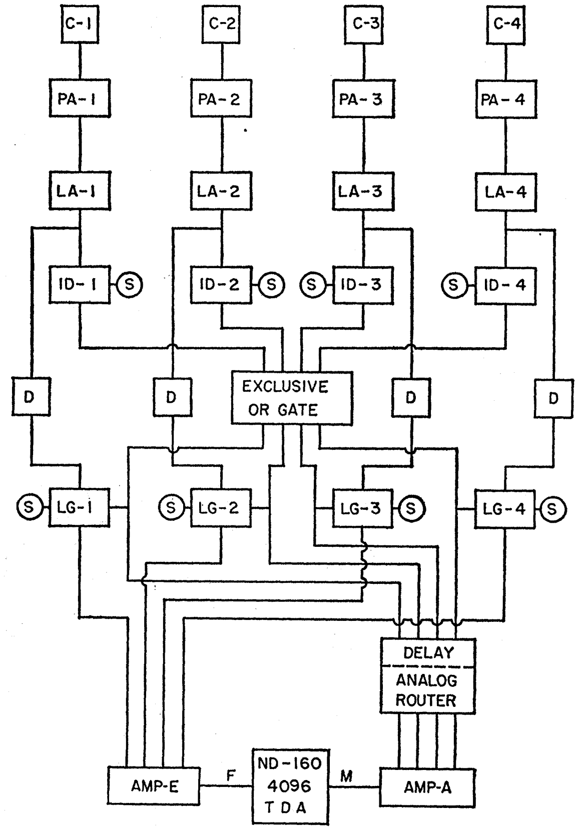

FIG. 1. Functional block diagram of the four-counter spectrometer system. The alphabetic designations for the components are defined as follows: C, silicon surface-barrier detector; PA, preamplifier; LA, linear amplifier; ID, integral discriminator; S, scaler; D, delay line; LG, linear gate; AMP-E, energy-pulse amplifier; AMP-A, analog-routing-pulse amplifier; and TDA, two-dimensional multichannel pulse-height analyzer.

[15] B. T. Lucas, S. W. Cosper, and O. E. Johnson, Phys. Rev. 133, B963 (1964).

[16] H. E. Wegner and W. S. Hall, Rev. Sci. Instr. 29, 1100 (1958).

[17] The exclusive OR gate, which was the essential logic element for this system, was designed by Prof. P. C. Simms, Purdue University, Lafayette, Ind.

[18] Model ND160, Nuclear Data Inc., Palatine, Ill.

[19] Types SBEI050-500 and SBCJ050-500, Oak Ridge Technical Enterprises Corp., Oak Ridge, Tenn.

[20] Yissum Research Development Company, Hebrew University, Jerusalem, Israel.

beam. No evidence was found for changes in target thickness.

Energy spectra were accumulated at 2.5° intervals over a laboratory angular range from about 15° to 100°. The counter biases were judiciously adjusted so as to discriminate against the detection of deuterons from the $C^{12}(He^3,d_0)N^{13}$ reaction. This deuteron group would have interfered with the observation of the α-particle groups associated with the production of the 4.32- and 4.81-MeV states of C^{11}.

III. EXPERIMENTAL RESULTS

The experimental differential cross sections for the $C^{12}(He^3,\alpha)C^{11}$ reactions leading to the ground, 2.00-, 4.32-, and 4.81-MeV states in C^{11} are shown in Figs. 2–5. The values of the cross sections have only been corrected to first order for finite geometry. The vertical bars on the experimental points (solid circles) represent the probable errors based on counting statistics only. When the error bars are not shown, it may be assumed that they are approximately the same size or smaller than the representative dots. The estimated limit of systematic error in the absolute cross sections, which is based on an appraisal of uncertainties in target thickness, beam integration, and experimental geometry, is ±15%.

Reliable cross sections for the $C^{12}(He^3,\alpha_1)C^{11}$ reaction could not be extracted from the experimental data for laboratory angles less than 25° because of the large uncertainties associated with the decomposition of the weak α_1 group from the extremely intense elastic He^3 group. Cross sections could not be determined for angles greater than about 100° because of the poorer resolution resulting from the reflection geometry and/or the interference of the elastic He^3 group with the α group of interest.

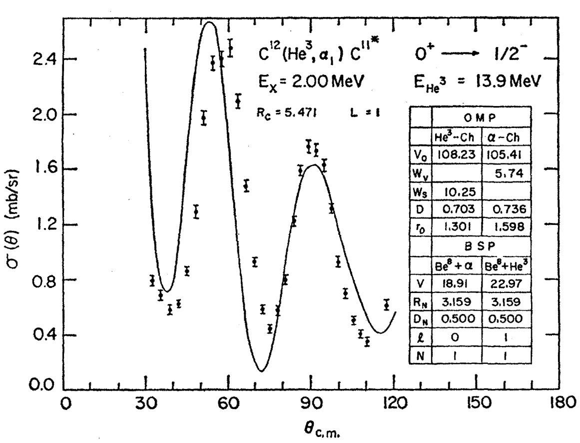

FIG. 2. Comparison between the experimental (solid circles) and best-fitting DWBA knockout (solid curve) angular distributions for the $C^{12}(He^3,\alpha_1)C^{11}$ reaction. The bound-state parameters (BSP), optical-model parameters (OMP), cutoff radius (R_C), and angular-momentum transfer (L) used in the calculation of the theoretical angular distribution are also tabulated. The calculated curve has been normalized to the experimental data so as to give a subjective, best over-all fit.

The integrated cross sections for the experimental angular distributions and the angular ranges over which the integrations were performed are shown in Table I. The integrated cross sections for the common angular range have been included to facilitate intercomparisons.

IV. ANALYSES

A. General

The 13.9-MeV $C^{12}(He^3,\alpha)C^{11}$ angular distributions were compared with those predicted by simple knockout and pickup models calculated in the zero-range DWBA by Tobocman.[21] Numerical evaluations of the differential cross sections were accomplished, using a slightly modified version of the computer code due to Gibbs *et al.*[22]

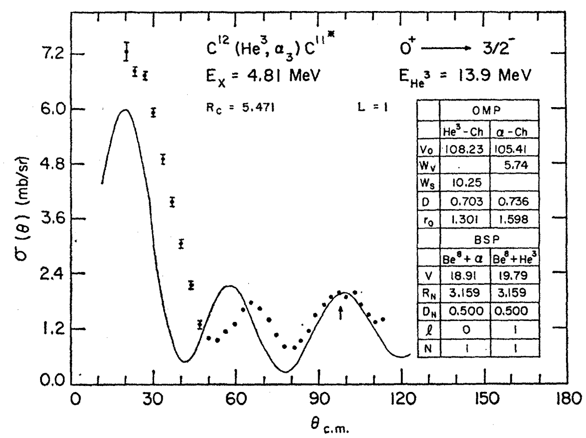

FIG. 3. The $C^{12}(He^3,\alpha_3)C^{11}$ experimental cross sections (solid circles) and the best-fitting DWBA knockout angular distribution (solid curve) that could be achieved using those optical-model parameters that yield the closest correspondence to the $C^{12}(He^3,\alpha_1)C^{11}$ data in the knockout analysis. The format of this figure is the same as that of Fig. 2, expect that the small arrow indicates the point of normalization.

The DWBA transition amplitude for the $I(He^3,\alpha)F$ reaction is

$$A_{He^3,\alpha}(\mathbf{K}_{He^3},\mathbf{K}_\alpha)=\langle\Phi_{\alpha,F}^{(-)}(\mathbf{K}_\alpha)\varphi_\alpha\varphi_F|V_{\alpha,F}-\bar{V}_{\alpha,F}| \times\Phi_{He^3,I}^{(+)}(\mathbf{K}_{He^3})\varphi_{He^3}\varphi_I\rangle, \quad (1)$$

where $\Phi_{He^3,I}^{(+)}$ and $\Phi_{\alpha,F}^{(-)}$ are the optical-model wave functions for the entrance and exit channels, respectively, the φ's are the internal wave functions of the various particles, $V_{\alpha,F}$ is the interaction potential for the α particle in the exit channel and the residual nucleus, and $\bar{V}_{\alpha,F}$ is the appropriate optical-model po-

[21] W. Tobocman, *Theory of Direct Nuclear Reactions* (Oxford University Press, London, 1961).

[22] W. R. Gibbs, V. A. Madsen, J. A. Miller, W. Tobocman, E. C. Cox, and L. Mowry, *Direct Reaction Calculation, NASA TN D-2170* (National Aeronautics and Space Administration, Washington, D. C., 1964).

tential which characterizes the elastic scattering of α particles from the final-state nucleus.

The optical-model (OM) wave functions were calculated using a total potential consisting of an optical potential derived from the general form

$$U(r)=-V_0f(r)-iW_vf(r)+i4DW_s\frac{d}{dr}f(r)\,, \qquad (2)$$

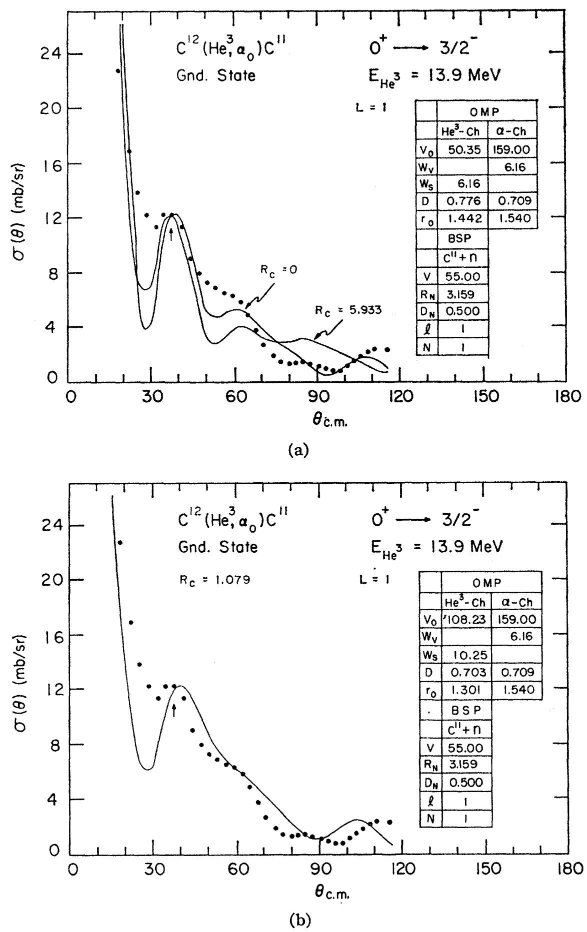

FIG. 4. Comparisons between the experimental (solid circles) and various DWBA pickup (solid curves) angular distributions for the $C^{12}(He^3,\alpha_0)C^{11}$ reaction. The general format of each part of this figure is the same as that of Fig. 3. In (a) are shown the pickup angular distribution judged to best represent the experimental data ($R_C=0$) and a similarly shaped pickup angular distribution having a nonzero cutoff radius ($R_C=5.933$ F). In (b) is shown the pickup angular distribution in closest correspondence with the experimental data when the optical-model parameters that yield the best pickup description of the α_2 angular distribution are used.

by setting either W_v or W_s equal to zero and taking

$$f(r)=1/(e^x+1)\,, \qquad (3)$$

where

$$x=(r-r_0A^{1/3})/D\,, \qquad (4)$$

and a repulsive Coulomb potential corresponding to a uniformly charged sphere of radius $1.2A^{1/3}$ F. The en-

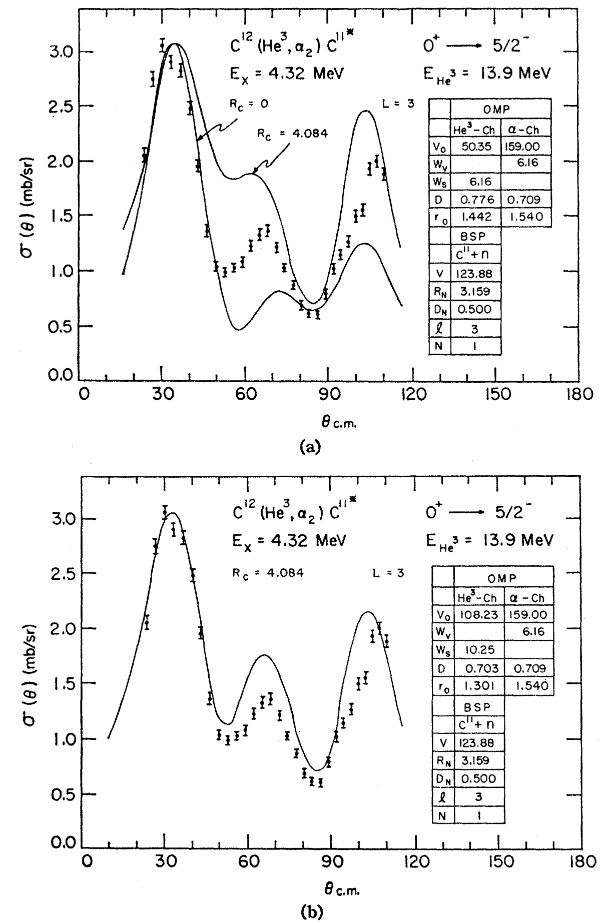

FIG. 5. Comparisons between the experimental (solid circles) and various DWBA pickup (solid curves) angular distributions for the $C^{12}(He^3,\alpha_2)C^{11}$ reaction. The general format of each part of this figure is the same as that of Fig. 3. In (a) are shown the two "best-fitting" curves obtained with those optical-model parameters that yield the best pickup description of the α_0 angular distribution (see the text for details). In (b) is shown the pickup fit judged to agree most closely with the α_2 angular distribution.

trance-channel OM parameters were extracted from data corresponding to the elastic scattering of He^3 from C^{12} at 13.9 MeV. The correct exit-channel description

TABLE I. Integrated 13.9-MeV cross sections for the $C^{12}(He^3,\alpha_n)C^{11}$ reactions.

Final state			Experimental		DWBA
No.	J_F^π	E_x (MeV)	Angular range (deg)	σ (mb)	σ^a (mb)
0	$\frac{3}{2}^-$	0	19.2–116.0	40.18	69.3
			31.8–111.8	30.50	
1	$\frac{1}{2}^-$	2.00	32.4–117.4	9.50	18.3
			32.4–110.2	9.15	
2	$\frac{5}{2}^-$	4.32	23.4–110.0	11.09	24.2
			33.3–110.0	9.65	
3	$\frac{3}{2}^-$	4.81	20.2–113.1	16.45	18.0
			33.6–110.6	11.94	

[a] These cross sections were calculated by integrating the best-fitting DWBA knockout or pickup angular distribution for each reaction over the angular range from 0° to 180°.

TABLE II. Entrance- and exit-channel optical-model parameters investigated in the DWBA analyses of the $C^{12}(He^3,\alpha)C^{11}$ reactions.

Reaction energy	V_0 (MeV)	W_v (MeV)	W_s (MeV)	D (F)	r_0 (F)
$C^{12}(He^3,He^3)C^{12}$ 13.9 MeV	50.35		6.16	0.776	1.442
	108.23		10.25	0.703	1.301
	189.12		14.41	0.663	1.212
$C^{12}(\alpha,\alpha)C^{12}$ [a] 18.0 MeV	105.41	5.74		0.736	1.598
	159.00	6.16		0.709	1.540

[a] These optical-model parameters were obtained from an analysis of the data of Ref. 23.

would require OM parameters corresponding to α-particle scattering from C^{11} at various energies in the interval from 11.1 to 17.7 MeV; since such data are not available, the exit-channel OM parameters used were derived from an analysis of the angular distribution for elastic α-particle scattering from C^{12} at 18.0 MeV, which had been measured by Corelli *et al.*[23] The various sets of OM parameters used in the analyses are given in Table II.

B. Knockout Analysis

The knockout model for a $C^{12}(He^3,\alpha)C^{11}$ reaction characterizes the initial- (final-) state nucleus as a two-body system made up of an α particle (He^3 particle) bound to a Be^8 nucleus. Since C^{12} and Be^8 are even-even nuclei and the incident particle has spin $\frac{1}{2}$, angular momentum and parity considerations yield single values for each of the relative orbital angular-momentum quantum numbers l and l' for these bound two-body systems. (The primed quantities refer to the final state.) Since $l=0$, the angular-momentum transfer L is equal to l'. The angular-momentum transfer has the values 1, 1, 3, and 1 for the reactions leading to the ground $(\frac{3}{2}^-)$, 2.00-MeV $(\frac{1}{2}^-)$, 4.32-MeV $(\frac{5}{2}^-)$, and 4.81-MeV $(\frac{3}{2}^-)$ states of C^{11}, respectively.

The bound-state wave functions φ_I and φ_F were calculated assuming a real Saxon-Woods potential. Since l (l') is given, as this model is formulated, the determination of the potential depth V (V') requires the specification of R_N and D_N (R_N' and D_N'), the well's geometric parameters, the radial quantum number N (N'), and the appropriate binding energy. The limitations of calculational practicality would not allow the full exploitation of the parametrization of the model; consequently the shape parameters were assigned physically reasonable values, $R_N=R_N'=3.159$ F[24] and $D_N=D_N'=0.500$ F. Although the only remaining continuously variable parameter available for adjustment in attempting to fit the experimental data is a lower cutoff radius R_C in the radial integrals, it should be pointed out that some freedom of choice may be exercised in the selection of the values of the bound-state radial quantum numbers and a combination of entrance- and exit-channel OM parameters.

The $C^{12}(He^3,\alpha_1)C^{11}$ angular distribution was analyzed first, in preference to the ground-state reaction, because of its pronounced and well-defined structure. For each of the six available combinations of OM parameters and the *a priori* reasonable assignments of $N=N'=1$, a series of calculations was performed in which the value of the cutoff radius was varied over the interval from 0.8 to 6.0 F. The zero-cutoff ($R_C=0$) cross sections bore no resemblance to the experimental data. Reasonable fits could be achieved with each combination of OM parameters for some value of R_C in the interval from 5.0 to 6.0 F. The calculated angular distribution which was judged to be in closest agreement with the experimental data is shown in Fig. 2. For completeness, similar investigations were made for the (N,N') combinations (1,2), (2,1), and (2,2), and $0.85\ \text{F}\leq R_C\leq R_N=3.159$ F. It was not necessary to investigate the region in which $R_C>R_N$, for each (N,N') combination, since the general shapes of the bound-state wave functions in the region outside the nuclear radius are insensitive to the radial quantum numbers. No satisfactory fits resulted.

A procedure identical to that described above was followed without success in attempting to reproduce the $C^{12}(He^3,\alpha_2)C^{11}$ data. The major shortcoming of the theoretical angular distributions was the total absence of a maximum in vicinity of 67°.

A similar analysis of the $C^{12}(He^3,\alpha_3)C^{11}$ data yielded the same conclusions as did the study of the $C^{12}(He^3,\alpha_1)C^{11}$ angular distribution. In particular, reasonable fits could be achieved with each of the combinations of OM parameters for some value of R_C in the interval 5.0 to 6.0 F. In Fig. 3 is shown the best representation of the α_3 data which could be achieved using the same combination of OM parameters that produced the best fit to the α_1 data.

An analysis of the $C^{12}(He^3,\alpha_0)C^{11}$ data, using the procedures described above, yielded no acceptable fits. The theoretical angular distributions all failed to predict the observed forward-angle behavior, particularly in the angular region from 35° to 40°.

C. Pickup Analysis

The pickup model for a $C^{12}(He^3,\alpha)C^{11}$ reaction characterizes the target nucleus as a neutron bound to an excited C^{11} core, where the state of the core is the same as that of the residual nucleus. Within the framework of this model, the ground-state wave function of C^{12} is some admixture of the wave functions corresponding to a neutron bound to various C^{11} cores; one such wave function for each excited state of C^{11}. Since the value of the cross section for a pickup reaction is simply related to that for the inverse process, a stripping reaction, by

[23] J. C. Corelli, E. Bleuler, and D. J. Tendam, Phys. Rev. **116**, 1184 (1959).

[24] Since the difference in the bound-state radii for C^{12} and C^{11} as determined from the expression $1.4A^{1/3}$ F is smaller than the grid size used in the integrations, the average value of 3.159 F was adopted for both nuclei.

the principle of detailed balance, it was convenient to evaluate the cross section in terms of the corresponding stripping model. A discussion of various aspects of the pickup reaction has been given by Hiebert *et al.*[25]

In this pickup-model description of the $C^{12}(He^3,\alpha)C^{11}$ reactions, the angular-momentum transfer is equal to the orbital angular momentum of the picked-up neutron, that is, $L=1$, 1, 3, and 1 for the reactions producing the ground ($\frac{3}{2}^-$), 2.00-MeV ($\frac{1}{2}^-$), 4.32-MeV ($\frac{5}{2}^-$), and 4.81-MeV ($\frac{3}{2}^-$) states of C^{11}, respectively.

A real Saxon-Woods potential was assumed for the various bound (C^{11*},n) systems. As the model is formulated, stipulation of the bound-state quantum numbers l and N, the shape parameters $R_N=3.159$ F and $D_N=0.500$ F, and the binding energy allows the determination of the well depth V and the wave function φ_I. The binding energy is taken to be equal to the mass difference between $C^{11*}+n$ and C^{12}, where n is the free-neutron mass and C^{11*} is the mass of the excited residual nucleus produced in the reaction.

For each of the four $C^{12}(He^3,\alpha)C^{11}$ reactions, assuming $N=1$, all the combinations of the OM parameters were tried for $R_C=0$ and various other values of R_C in the range from 0.85 F to R_x ($R_x=7.32$ F for the ground-state reaction and $R_x=5.01$ F for the excited-state reactions). Similar investigations were made for $N=2$ in the cases of those reactions leading to the lowest three excited states of C^{11}.

In Fig. 4(a) is shown the calculated angular distribution which best represents the $C^{12}(He^3,\alpha_0)C^{11}$ experimental data ($R_C=0$). The second curve ($R_C=5.933$ F) has a similar forward-angle shape, but it is a poorer over-all representation of the data. This is the only case in which there was any resemblance between the experimental and the zero-cutoff angular distributions. In Fig. 4(b) is shown that theoretical curve which best represents the $C^{12}(He^3,\alpha_0)C^{11}$ data when the OM parameters that produce the best fit to the $C^{12}(He^3,\alpha_2)C^{11}$ data [see Fig. 5(b)] are used.

No fit to the $C^{12}(He^3,\alpha_1)C^{11}$ angular distribution could be achieved which was comparable in quality to that attained with the knockout model. The angular distributions calculated from the pickup model which had a shape similar to the experimental angular distribution had oscillations which were completely out of phase with it.

The calculated angular distributions shown in Fig. 5(a) are those which correspond most closely to the $C^{12}(He^3,\alpha_2)C^{11}$ data when the same OM parameters that produced the best fits to the $C^{12}(He^3,\alpha_0)C^{11}$ data [see Fig. 4(a)] are used. The shapes of these two curves tend to suggest that some intermediate value of R_C might yield a better representation of the data; however, detailed calculations have shown that this does not occur. In Fig. 5(b) is shown the calculated angular distribution which gives the best representation of the $C^{12}(He^3,\alpha_2)C^{11}$ data. The OM parameters correspond to those used in the calculation of the curve shown in Fig. 4(b).

Even the gross features of the $C^{12}(He^3,\alpha_3)C^{11}$ angular distribution could not be reproduced by the pickup model using the OM parameters of Table II.

V. DISCUSSION

Each experimental 13.9-MeV $C^{12}(He^3,\alpha)C^{11}$ angular distribution exhibits an oscillatory structure and/or forward-angle peaking which suggest(s) that a DR mechanism is at least operative, if not dominant (see Figs. 2–5). Although questions concerning the relative importance of the operative DR and CN mechanisms cannot be answered with certainty without a detailed study of the energy dependence of the cross sections, reaction systematics do indicate that the relative importance of the DR mechanism increases with increasing energy. Since the DR mechanism appears to be a major contributor to the reaction cross sections at 10 MeV,[3,4] it is likely to have an even larger relative strength at 13.9 MeV. Because of the lack of experimental information on the energy dependence of these reactions, any stronger statements than the preceding ones concerning the relative strength of the DR mechanism would be untenable.

The 13.9-MeV α_0 angular distribution exhibits strong forward-angle peaking and a rather weak, washed-out oscillatory structure. It is distinctly different in general character than that of the angular distributions associated with the excited states. Its gross structure is somewhat similar to that of the α_0 angular distributions observed at 10 [3,4] and 26.1 MeV.[10] For the common angular range, the integrated 10-, 13.9-, and 26.1-MeV α_0 cross sections decrease with increasing energy. The general shape of the 13.9-MeV α_1 angular distribution is similar to that observed at 10 MeV, [3] except that at 13.9 MeV the oscillations are shifted toward smaller angles. For the angular range common to the 10- and 13.9-MeV data, the integrated cross sections are approximately equal.

Comparisons of the experimental 13.9-MeV $C^{12}(He^3,\alpha)$ C^{11} angular distributions with those associated with the production of the corresponding mirror states in the $C^{12}(t,\alpha)B^{11}$ reactions at the incident energies of 10.06 [26] and 12.95 MeV [27] reveal a remarkable similarity in both shape and magnitude. While this result may be initially somewhat unexpected, in view of the dissimilarity of the corresponding 13.9- and 10-MeV $C^{12}(He^3,\alpha)C^{11}$ angular distributions, it can be rationalized. Except for Coulomb effects, the properties of the corresponding final states in the mirror nuclei C^{11} and B^{11} may be expected

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to be very similar. For the states of interest, the exit-channel energies for the $C^{12}(t,\alpha)B^{11}$ reactions are from 1.5 to 1.8 MeV lower and from 0.8 to 1.2 MeV higher at the initiating energies 10.06 and 12.95 MeV, respectively, than those of the 13.9-MeV $C^{12}(He^3,\alpha)C^{11}$ reactions. On the other hand, the exit-channel energies for the 10-MeV $C^{12}(He^3,\alpha)C^{11}$ reactions are about 4.2 MeV lower than those for the 13.9-MeV $C^{12}(He^3,\alpha)$ C^{11} reactions. While the entrance channels for the 10-MeV (t,α) and (He^3,α) reactions may be very similar, because of the closer correspondence in exit-channel energy, the 10-MeV (t,α) exit channel is likely to more closely resemble the 13.9-MeV (He^3,α) exit channel. On this basis, a closer correspondence between the 10-MeV (t,α) and 13.9-MeV (He^3,α) angular distributions would be expected. Extending this line of reasoning, it may be concluded that the 12.95-MeV (t,α) and 13.9-MeV (He^3,α) angular distributions should have the most similar shapes. This is consistent with the experimental results.

To the extent that the strengths of the $C^{12}(He^3,\alpha)C^{11}$ reactions may be inferred from partial integrated cross sections, those producing the lowest three excited states of C^{11} are of about equal strength and are about one-third of that which produces the ground state (see Table I). Note that Gray *et al.*[5] state in a preliminary report that the α_1, α_2, and α_3 cross sections are of comparable magnitude for incident energies of 16, 17, and 18 MeV.

Since the best-fitting DWBA angular distributions of the present study provide a good representation of the 10.06-MeV $C^{12}(t,\alpha)B^{11}$ angular distributions which have been measured over a wide angular range (about 7° to 175°) by Pullen *et al.*,[26] and since the 10.06-MeV $C^{12}(t,\alpha)B^{11}$ and 13.9-MeV $C^{12}(He^3,\alpha)C^{11}$ angular distributions for these analog reactions are very similar in shape over their common angular range, then the 0°–180° integrated DWBA cross sections should be a good approximation to the actual integrated cross sections for the 13.9-MeV $C^{12}(He^3,\alpha)C^{11}$ reactions (see Table I). Using these DWBA cross sections, one finds $\sigma(\alpha_0)=3.79\sigma(\alpha_1)=2.86\sigma(\alpha_2)=3.85\sigma(\alpha_3)$. In measuring the excitation function for the $C^{12}(He^3,\alpha)C^{11}$ reaction, using a stacked-foil technique, Cochran and Knight[14] found the reaction cross section in the vicinity of 14 MeV to be 190 mb. Consequently it may be concluded that the cross section for producing all the excited states above 4.81 MeV which are stable to heavy-particle emission is less than about 60 mb. The total reaction and elastic scattering cross sections as determined in the OM analyses are approximately 1000 and 600 mb, respectively.

As indicated in Sec. I, the assumption that the ground state of C^{12} is made up of $(1s)^4(1p)^8$ configurations leads to an impasse in explaining the production of the second excited state of C^{11} ($\frac{5}{2}^-$, 4.32 MeV) through a simple pickup mechanism. Two explanations for the production of the 4.32-MeV state by pickup have been proposed.[28] (a) An inelastic process is operative in which the C^{12} nucleus is excited to its first excited state (2^+, 4.435 MeV) and then a neutron is picked up from this excited state. Assuming an $L=1$ transition, $\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{5}{2}^-$, or $\frac{7}{2}^-$ states may be produced. (b) The ground state of C^{12} is made up of configurations involving higher orbitals. The first proposal cannot be definitely ruled out; however, it does not seem likely that such a two-step process could yield a cross section as large as those observed in various pickup reactions. In view of the deformation of the C^{12} nucleus in its ground state, it is reasonable that the original assumption concerning the configuration mixture be altered. In connection with DWBA analyses of C^{12} $(p,d)C^{11}$ reactions, it has been suggested by Towner[28] that the two-particle–two-hole description of C^{12} given by Goswami and Pal[29] be considered. In contradiction to the present experimental results, the spectroscopic factors calculated from these ground-state wave functions indicate that the 4.32-MeV state of C^{11} should only be weakly produced in a pickup reaction.[28]

The most striking result of the DWBA analyses of the present study is the fact that the angular distributions associated with the α_0 and α_2 groups could only be fitted with the pickup model, and those associated with the α_1 and α_3 groups could only be fitted with the knockout model. Since the angular distributions associated with the production of the first and third excited states are similar in shape, and since both correspond to $L=1$ angular-momentum transfer, it is not surprising that a given model will fit either both or neither of them. The need for two models to describe these four $C^{12}(He^3,\alpha)C^{11}$ angular distributions is somewhat disturbing. Although the present study has yielded no satisfactory explanation or interpretation of this result, one interesting possibility has been considered. Most interpretations and analyses of experimental results for reactions in which pickup and knockout may be considered to be competing processes usually presume that the knockout mechanism is a negligible contributor to the cross section. Although the experimental facts may support this as a useful generalization with a wide range of applicability, the possibility of exceptions cannot be excluded. One might speculate as to whether the $C^{12}(He^3,\alpha)C^{11}$ reaction is such an exception, since the α-cluster character of C^{12} would favor the knockout process, while its "single-particle" character would presumably favor the pickup reaction. In drawing such a conclusion, caution should be exercised, since the relative importance of each reaction mechanism in the production of a given final state is dependent on the character of both the initial and final states, and the α-cluster character of the states of C^{11} may vary from state to state. Assuming no interference, the cross section associated with the production of a given final state would

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[29] A. Goswami and M. K. Pal, Nucl. Phys. **44**, 294 (1963).

be an incoherent sum of the pickup and knockout contributions. The admixture would, of course, be determined by the character of the two states involved; consequently, under appropriate circumstances, the contribution of one mechanism or the other might be negligible for the production of different final states in the same nucleus. If one ignores the failure of the "single-particle" wave function to account for the large cross section associated with production of the second excited state of C^{11}, an interpretation of the results of these DWBA analyses from this point of view leads to the following conclusions concerning the states of C^{11}: (a) The first and third excited states have a strong α-cluster character; (b) the second excited state has a dominant "single-particle" character; (c) because of different over-all structure of the α_0 angular distribution, the ground state may be of "single-particle" character with a non-negligible α-cluster admixture. Of course, this interpretation presumes that interference effects are negligible, an assumption which may be valid, but for which there is no *a priori* justification. Within the context of the present study, these ideas are audacious speculations; however, they are intriguing, and an extended theoretical and experimental investigation would be of considerable interest.

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Theoretical Fission-Antineutrino Spectrum and Cross Section of the Reaction $^3He(\bar{\nu}_e,e^+)^3H$†

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The energy spectrum of antineutrinos emitted by binary fission fragments of uranium-235 in secular equilibrium was calculated. The primary fission yields used in this work were calculated, using the primary fission product charge distributions due to A. C. Wahl. The total number of antineutrinos per fission predicted with the calculated spectrum is 6.06. The antineutrino spectrum derived in this work was used to calculate the average cross section for the reaction $p(\bar{\nu}_e,e^+)n$ and $^3He(\bar{\nu}_e,e^+)^3H$. The cross sections are 1.09×10^{-43} cm²/(fission $\bar{\nu}$) and 2.46×10^{-43} cm²/(fission $\bar{\nu}$), respectively.

I. INTRODUCTION

IN 1957 Lee and Yang[1] pointed out that the cross section for inverse β decay provides a further test of the two-component neutrino theory. More specifically, the cross section predicted by the two-component theory is twice as large as that predicted by the four-component theory with parity conservation. Direct measurements of the cross section for the reaction $p(\bar{\nu}_e,e^+)n$ were reported by Cowan *et al.*,[2] by Reines and Cowan,[3] and more recently by Nezrick and Reines.[4] References 3 and 4 conclude that the measured cross sections are consistent with the two-component neutrino description; however, the accuracy of the values reported in Refs. 2 and 3 is described as marginal[4] because of uncertainties in the energy spectrum of antineutrinos from the reactor. It has been suggested[4,5] that an independent experiment involving the reaction $^3He(\bar{\nu}_e,e^+)^3H$ would be very useful in removing some of the uncertainties in the conclusions of prior inverse β-decay experiments. The feasibility of measuring the cross section for the inverse β decay of ^3He is presently under study at the University of South Carolina. An important part of this study is the theoretical prediction of the cross section for this reaction which is the subject of this work.

Uncertainties in the measured cross section of the inverse β decay of ^1H and ^3He are partly due to the extremely small value of the cross section ($\sim10^{-43}$ cm²) and partly to a lack of knowledge of the energy spectrum of incident antineutrinos. Thus, any comparison of the measured and predicted reaction rates is frustrated to the extent that the spectrum is uncertain.

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