Study of C^{12} States Using the $B^{11}(He^3, d)C^{12}$ Reaction*

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States in C^{12} have been studied using the $B^{11}(He^3, d)C^{12}$ reaction at a He^3 energy of 44.0 MeV. Energy spectra were obtained to 26-MeV excitation in C^{12}. The results indicate the presence of a positive-parity state at 11.16 ± 0.05 MeV having a width of 550 ± 100 keV. It is suggested to be the 2^+ member of an α-cluster band based on the 0^+ state at 7.65 MeV. There is no evidence of a state at 14.7 MeV. The 4^-, $(p_{3/2})^{-1}(d_{5/2})$ $T=0$ and $T=1$ states are located at 18.27 and 19.56 MeV, respectively. In the region of the giant dipole resonance in C^{12}, there is a peak at 22.4 MeV.

I. INTRODUCTION

Although numerous studies have been made of the level structure of C^{12}, questions still remain about some of the bound states. For example, the cluster model[1,2] which does well in other light nuclei, does not fare well in C^{12}. In particular, the model predicts a pair of 2^+ states around 11 MeV, one of them being a member of a 0^+ to 6^+ α-cluster band based on the 0^+ state at 7.65 MeV. The latest level diagram appears in Fig. 1(a). Instead of a pair of 2^+ states around 11 MeV there is only one broad positive-parity state, with a suggested spin of 0^+. It has previously been suggested that the broad state at 10.3 MeV is one of the predicted 2^+ states, the one that is not the member of the band.[3] Another state in this region, at an energy of 11.1 MeV, was reported earlier,[4] but was later refuted,[5] and is not listed in the latest tabulation.[6] There is uncertainty about the state at 14.7 MeV, since it has only been reported once, in a lower-energy $B^{11}(He^3, d)C^{12}$ study.[7] In addition, some of the calculated single-particle single-hole states[8] have not yet been located.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Energy spectra of deuterons from the $B^{11}(He^3, d)C^{12}$ reaction were obtained from the ground state to 26-MeV excitation in C^{12}, using a 44.0-MeV He^3 beam from the University of Michigan 83-in. sector-focused cyclotron. Nuclear-emulsion plates in the focal plane of a double-focusing 180° magnetic spectrometer were used to detect the deuterons. Self-supporting enriched B^{11} targets, about 200-$\mu g/cm^2$ thick, were obtained from Oak Ridge National Laboratory. A spectrum is shown in Fig. 2 and the angular distributions are in Fig. 3. The error bars include errors due to statistics and background subtraction.

The results indicate the presence of a state at 11.16 ± 0.05 MeV. Figure 4 concentrates on the 11-MeV region. As the figure shows, the reason the 11.16-MeV state is visible is that at a He^3 energy of 44 MeV the cross section of the 10.84-MeV 1^-, $(p_{3/2})^{-1}(s_{1/2})$ state is very small between 25 and 35°. Because of the simple structure of the 10.84-MeV state, the cross section of any stripping or inelastic scattering reaction populating the state is usually large, making it difficult to resolve a small broad peak at 11.16 MeV. The measured width of the 11.16-MeV state is 550 ± 100 keV. It has an $l=1$ angular distribution, indicating positive parity. No model predicts another 1^+ state in this region. Considering the $(2J+1)$ factor in the stripping cross section, and the large yield of the 11.16-MeV state compared to the 0^+ state at 7.65 MeV, a spin of 2^+ is suggested. If, as is suggested here, the 11.16-MeV state is the predicted 2^+ member of the α-cluster band,[1] then $J(J+1)$ spacing would predict the 4^+ state to lie at 19.4 MeV. There would be very small probability of populating the 4^+ state in this study. However, there is a listed level in C^{12} at 19.39 MeV with suggested parameters of even-spin, even-parity, $T=0$, and a width of 1.1 MeV. This is a likely candidate for the broad 4^+ $T=0$ member of the α-cluster band. Assuming $J(J+1)$ spacing again, the excitation energy of the 6^+ member would be about 32.2 MeV.

Because of the large width of the state at 13.35 MeV, a complete angular distribution could not be obtained, leaving the configuration of the state still uncertain.

Another result shown in Fig. 1(b) is the omission of the 14.71-MeV state. The state has only been reported once, as a narrow peak in a lower-energy (He^3, d) study.[6,7] There was no indication of the state at any angle. At a lab angle of 12.5° the yield of a state at 14.7 MeV would be less than 2% that of the 15.11-MeV state.

A pair of states in C^{12} that have not previously been located are the 4^-, $(p_{3/2})^{-1}(d_{5/2})$ $T=0$ and $T=1$ states. Because of the $(2J+1)$ factor in the stripping cross section, these states should be very prominent in the spectra. They should ap-

pear around 18 MeV, the approximate unperturbed energy of the $(p_{3/2})^{-1}(d_{5/2})$ configuration, since there are no other nearby 4^- states to mix with. From the shape of the spectra there appear to be four states contributing in the 18- and 19-MeV region. The peak at 18.27 ± 0.05 MeV, having a width of 350 ± 50 keV, is suggested to be the 4^- $T=0$ state, and the peak at 19.56 ± 0.05 MeV, having a width of 500 ± 80 keV, is suggested to be the 4^- $T=1$ state. As shown in Table I these two levels have the largest, and approximately equal, lab cross sections at 10°. The median energy of these two states is 18.9 MeV, somewhat higher than the unperturbed $(p_{3/2})^{-1}(d_{5/2})$ energy of 17.6 MeV used in the particle-hole calculations.[8] The peak at 18.38 MeV is very likely the 3^-, $T=1$, $(p_{3/2})^{-1}(d_{5/2})$ state.[9] There is also a significant contribution around 19.2 MeV. Because of the high background from three-body breakup, angular distributions were not obtained for any states above 16.11 MeV. The suggested spin assignments are based mainly on a relative comparison of peak intensities with those of known states with the same configuration using $(2J+1)$ as the cross-section weighting factor.

Two peaks were observed between 20- and 26-MeV excitation in C^{12} in the presence of a heavy three-body-breakup background. The first peak, at 20.6 MeV, has a width of 250 ± 50 keV. The second peak, at 22.40 ± 0.08 MeV, has a width of 350 ± 50 keV. From the energy and the magnitude of the cross section, the suggested configuration of the 22.4-MeV peak is 1^-, $T=1$, $(p_{3/2})^{-1}(d_{5/2})$, which is the state that gets most of the dipole strength in the particle-hole calculations.[8] For comparison with photonuclear measurements it should be noted that the shapes of the measured (γ, n) and (γ, p) excitation functions differ in the region of the giant resonance in C^{12}. The (γ, p) cross section has a broad maximum centered about 22.4 MeV, whereas the (γ, n) cross section exhibits two peaks,[6] at 22.0 and 23.5 MeV. Thus both the $B^{11}(He^3, d)C^{12}$ and $C^{12}(\gamma, p)B^{11}$ reactions have a peak at approximately 22.4 MeV, while the $C^{12}(\gamma, n)C^{11}$ reaction has a local minimum at the same energy.

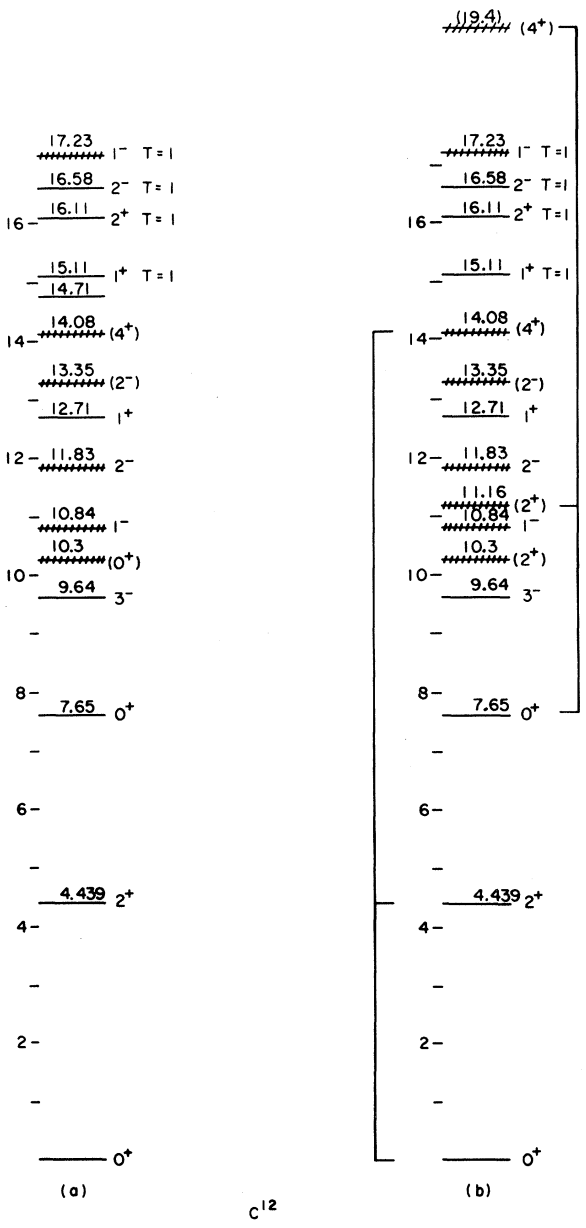

FIG. 1. Partial energy level diagram for C^{12}. Column (a) is from Ref. 6; column (b) includes changes suggested by the present results. Energies are in MeV.

TABLE I. States in C^{12} observed with the $B^{11}(He^3, d)$-C^{12} reaction at 44 MeV.

Energy (MeV)	J	T	Γ (keV)	l_j	$\sigma(\theta)$ lab at 10° (mb/sr)	S	Relative S
g.s.	0^+	0		$p_{3/2}$	3.70	4.25	1.0
4.44	2^+	0		$p_{1/2}$	3.80	0.61	0.14
7.65	0^+	0		$p_{3/2}$	0.07	0.06	0.014
9.64	3^-	0		$d_{5/2}$	2.84	0.22	0.052
10.84	1^-	0	350 ± 40	$s_{1/2}$	0.90	0.87	0.20
11.16	(2^+)	0	550 ± 100	$(p_{1/2})$	0.96	0.11	0.026
11.83	2^-	0	290 ± 40	$d_{5/2}$	0.69	0.13	0.031
12.71	1^+	0		$p_{1/2}$	3.62	0.78	0.18
13.35	(2^-)	0	500 ± 80	$(s_{1/2})$			
15.11	1^+	1		$p_{1/2}$	2.80	0.72	0.17
16.11	2^+	1		$p_{1/2}$	4.78	0.88	0.21
18.27	(4^-)	(0)	350 ± 50	$(d_{5/2})$	10.7		
18.36	(3^-)	(1)	270 ± 50	$(d_{5/2})$	7.1		
19.2	(2^-)	(1)		$(d_{5/2})$	5.4		
19.56	(4^-)	(1)	500 ± 80	$(d_{5/2})$	10.8		
20.6	(3^-)	(0)	250 ± 50	$(d_{3/2})$	0.90		
22.4	(1^-)	(1)	350 ± 50	$(d_{5/2})$	1.9		

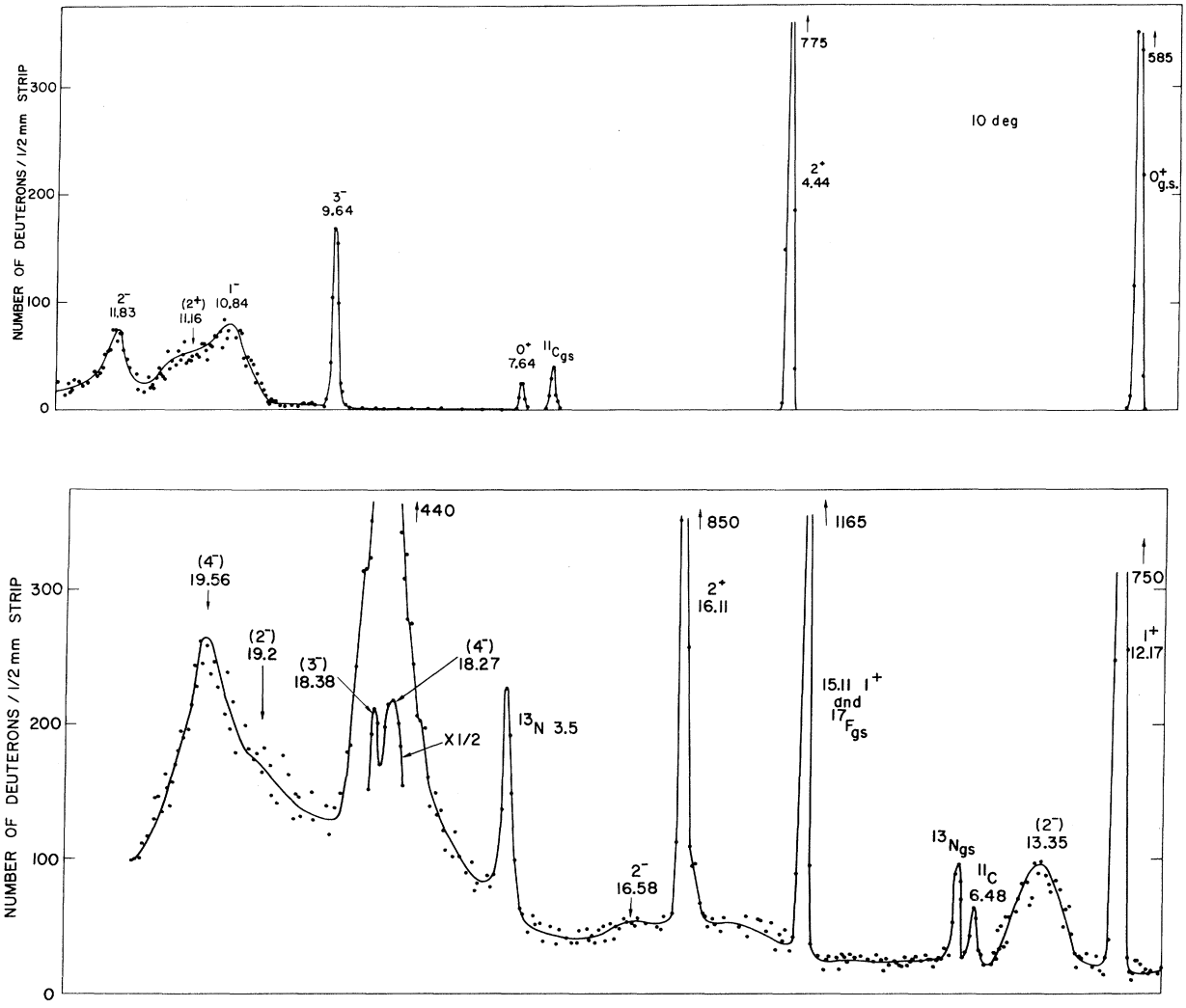

FIG. 2. Deuteron energy spectrum from the reaction $B^{11}(He^3, d)C^{12}$. Energies are in MeV.

TABLE II. Optical-model parameters used in the DWBA calculations.

Particle	V (MeV)	W[a] (MeV)	r_0 (F)	a (F)	r_0' (F)	a' (F)
He^3[b]	169.0	32.1	1.14	0.675	1.82	0.566
d[c]	92.4	9.75	1.04	0.788	1.43	0.693

[a]Volume absorption.
[b]See Ref. 10.
[c]E. Newman, L. C. Becker, B. M. Preedom, and J. C. Hiebert, Nucl. Phys. A100, 225 (1967).

TABLE III. Sum rules applied to the $p_{3/2}$ and $p_{1/2}$ transitions.

State		$G(p_{3/2})$	$G(p_{1/2})$ $T=0$	$G(p_{1/2})$ $T=1$
g.s.	0^+	0.53		
7.65	0^+	0.01		
4.44	2^+		0.38	
11.16	(2^+)		0.07	
12.71	1^+		0.30	
15.11	1^+			0.27
16.11	2^+			0.55
	Totals	0.54	0.75	0.82

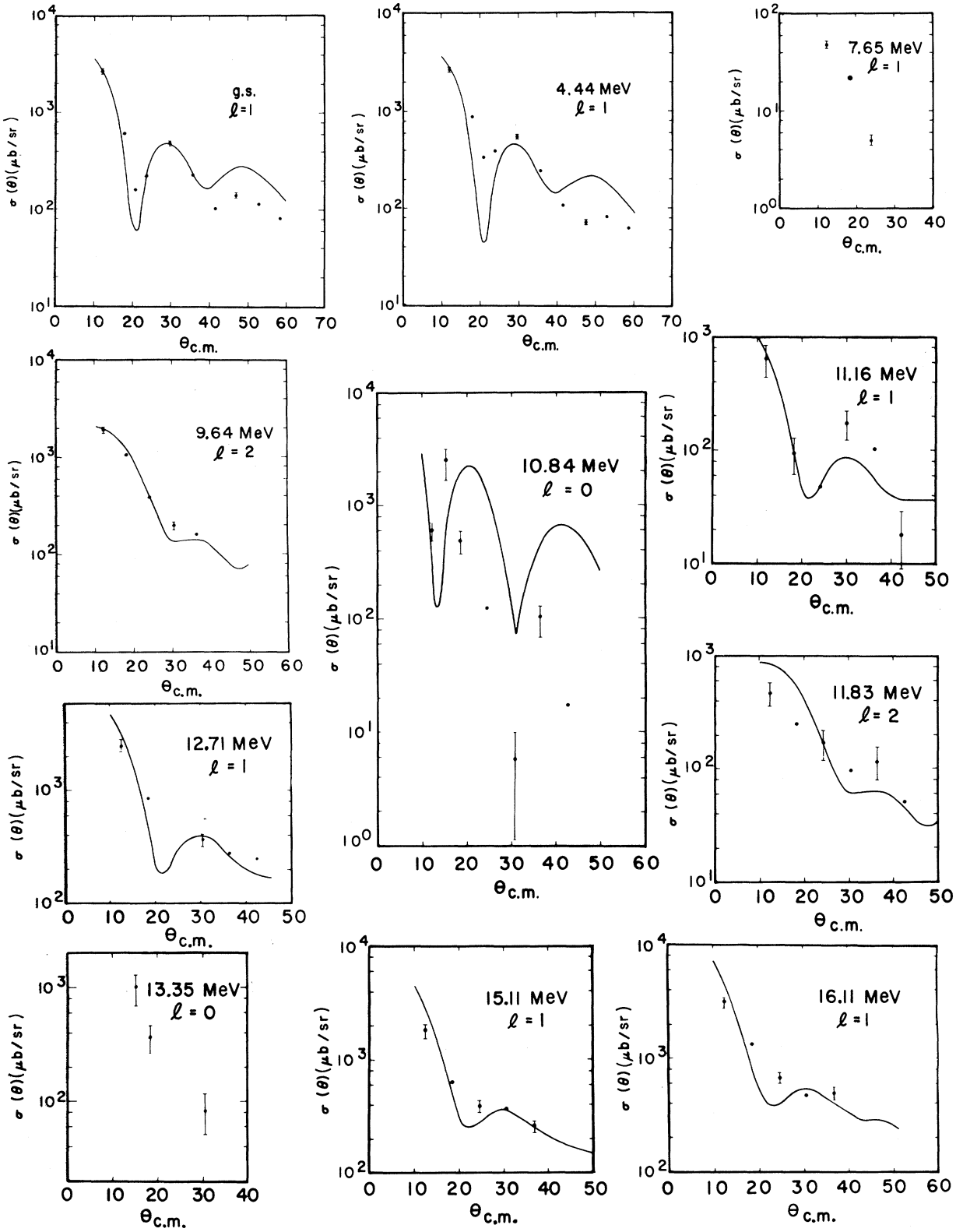

FIG. 3. Angular distributions of deuterons from the reaction $B^{11}(He^3, d)C^{12}$. The solid lines were obtained using the DWBA program JULIE.

III. DWBA ANALYSIS

The Oak Ridge program JULIE was used to calculate the distorted-wave angular distributions in Fig. 3. The calculations utilized a zero-range modified Born approximation with no radial cutoff. Optical-model parameters for the entrance and exit channels are listed in Table II. The bound-state wave functions were computed with a Woods-Saxon well with parameters $r = 1.2$ F, $r_C = 1.2$ F, $a = 0.7$ F, and spin-orbit parameter $\lambda = 25$. The depth of the well was adjusted to give the measured separation energy.

The inclusion of a spin-orbit potential for the exit channel had no significant effect on either the shape or magnitude of the calculated angular distributions. Spin-orbit effects were also neglected in the entrance channel.[10] The separation energy for the unbound state at 16.11 MeV was assumed to be the same as that for the 15.11-MeV state.

The differential cross section is given by

$$\frac{d\sigma}{d\Omega} = x \frac{2J+1}{2J_0+1} C^2 \sum_l S_l \Phi^l , \tag{1}$$

where J_0 and J are the spins of the initial and final states, C is the isobaric-spin Clebsch-Gordan coupling factor, l is the orbital angular momentum transfer, S_l is the spectroscopic factor, and Φ_l is the cross section calculated by the DWBA code. For all transitions studied here, $C^2 = \frac{1}{2}$. A value of 4.4 was used for the normalization factor x.[11] The spectroscopic factors obtained from the calculated angular distributions in Fig. 3 are listed in Table I. A single l value is assumed for each transition.

Each transition has a strength associated with it defined by

$$G_{lj} = \frac{2J+1}{2J_0+1} C^2 S_{lj} . \tag{2}$$

The sum rules that apply in this study are, for the $p_{3/2}$ transitions, $\sum G_{lj} = 1$, and, for the $p_{1/2}$ transitions, $\sum G_{lj} = 1$ for both $T = 0$ and $T = 1$. Sum rules for the $d_{5/2}$ and higher configurations are not given, since all of the states were not observed. With the assumption of no configuration mixing the sum rules predict a spectroscopic factor of 8 for the ground-state transition and 1 for all the other transitions. The observed spectroscopic factors in Table I are all smaller than these predicted values. The strengths calculated from the present results are shown in Table III. All three sums are smaller than the theoretical values.

The small values of the spectroscopic factors of the 0^+ and 2^+ cluster states at 7.65 and 11.16 MeV are expected. However, the spectroscopic factors of the 3^- and 2^- states at 9.64 and 11.83 MeV are also much smaller than the value of 1.0 predicted by the simple model. Negative-parity states in this region of excitation are predicted by the cluster model.[1,2]

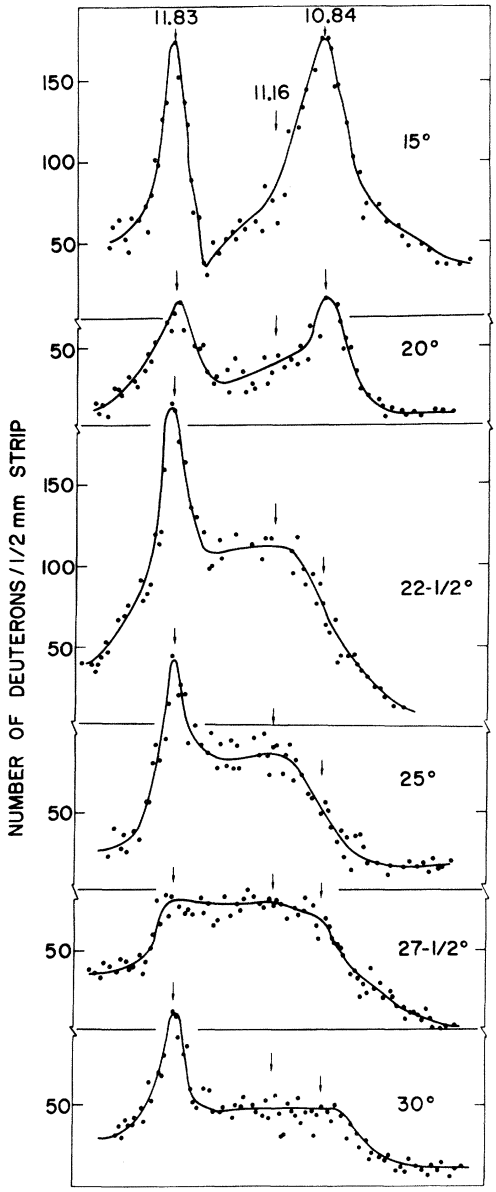

FIG. 4. Energy spectra of deuterons in the 11-MeV region of C^{12}.

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Isomer Ratio for (b, xn, yp, γ) Reactions

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A method for the calculation of isomer ratios in reactions in which the compound nucleus decays by the emission of a few particles followed by γ emission is presented. It is shown that the calculated value of the isomer ratio is sensitive to the spin cutoff parameter, the amount of quadrupole admixture in the γ-ray cascade, and the presence of discrete levels. In most cases good agreement between experimentally measured and calculated values of isomer ratios is obtained.

I. INTRODUCTION

In this paper a new method for the calculation of isomer ratios for reactions in which a compound nucleus decays emitting several particles and γ rays is presented. The method allows for more accurate evaluation of isomer ratios and a more meaningful interpretation of these ratios.

Huizenga and Vandenbosch[1,2] were the first to realize that the isomer ratio depends not only on the properties of the initial state, the ground state, and isomeric state, but also on the properties of the intermediate states. Consequently they suggested a method for the calculation of isomer ratios. To simplify the computation, Huizenga and Vandenbosch[1,2] suggested an approximate method for the calculation of isomer ratios. The Huizenga-Vandenbosch approximation is based on the following assumptions: (i) The isomeric and ground state are populated only in the last state of the γ-ray cascade. (ii) In this final step, transitions with smaller spin change predominate. (iii) The number of γ rays in the cascade is introduced as a free parameter. (iv) In the γ-ray cascade only dipole radiation is considered except in the final transition. (v) The energy dependence of the density of levels is neglected. (vi) The effects of all discrete states, except the isomeric and ground state, are not considered. (vii) For each step in the evaporation, only the dominant decay is considered and competing decays are neglected. Yet despite its limitations the Huizenga-Vandenbosch method serves as a very good approximation.

Recently studies of isomer ratios were reported[3-6] which exclude some of the limitations imposed by the Huizenga-Vandenbosch[1,2] approximation. In particular, one of the present authors[6] developed a method for the evaluation of isomer ratios for (n, γ) reactions which eliminates most of these assumptions. This method was successfully applied[7] to the analysis of isomer ratios in such reactions. The method discussed in this paper is a generalization of the previous work.[6] The present method avoids all the limitations implied by the Huizenga-Vandenbosch[1,2] approximation and is applicable to the most complex reactions. First, the cross section for the formation of the compound nucleus as a function of spin and energy is