States in C^{12} Between 16.4 and 19.6 MeV*

R. E. SEGEL, S. S. HANNA,† AND R. G. ALLAS‡
Argonne National Laboratory, Argonne, Illinois
(Received 7 April 1965)

The states of C^{12} in the energy region 16.4 MeV $< E_x(C^{12*}) <$ 19.6 MeV have been studied by bombarding B^{11} with protons in the range 0.5 MeV $< E_p <$ 4.0 MeV. Many angular distributions and yield curves were measured for the capture gamma rays forming the ground state and first excited state of C^{12} and for the alpha-particle transitions to the ground state and first excited state of Be^8. The total-neutron-yield curve was determined by measuring the yield of residual C^{11} activity. The absolute inelastic proton-scattering cross section was also determined and used to normalize the relative-yield curve of other investigators. The elastic proton scattering was measured as a function of energy at several angles. Some γ-γ angular-correlation measurements were made at one resonance. In all, nine distinct resonances were studied and given spin, parity, and isospin assignments with varying degrees of completeness. In most cases in which earlier assignments had been made, these assignments were confirmed. The observed levels are compared with those predicted by particle-hole calculations. It is concluded that the particle-hole model is consistent with most of the observed structure, and that all of the predicted levels in this region have been at least tentatively identified.

I. INTRODUCTION

THE binding energy of a proton in C^{12} is 15.96 MeV; therefore levels above this threshold can be formed by bombarding B^{11} with protons. Although C^{12} contains few nucleons and perhaps has a high degree of symmetry, one still expects many levels at these high excitation energies and, indeed, previous experimental investigations have displayed complex structure.[1] This complexity is partially alleviated by the fact that a wealth of information can be rather easily gathered to aid the interpretation. In addition to the omnipresent capture gamma rays, elastically scattered protons, and alpha particles forming the ground state and first excited state of Be^8, the inelastic-proton channel opens at $E_p = 2.32$ MeV and the neutron channel at $E_p = 3.02$ MeV. The relevant energy-level diagram is given in Fig. 1.

In the present work the states in C^{12} between 16.4 and 19.6 MeV have been examined by bombarding B^{11} with protons in the energy range 0.5–4.0 MeV. Two capture gamma rays, two alpha-particle groups, neutrons (detected by the residual C^{11} activity), gamma rays following inelastic scattering, and elastically scattered protons were all observed. The gamma rays following inelastic scattering, which in this energy region can only involve the first excited state of B^{11} at 2.13 MeV, were not extensively studied because a yield curve for these gamma rays has already been measured[2] and their angular distribution must be isotropic since the spin of the state is $\frac{1}{2}$. However, the absolute cross section for the production of these gamma rays was measured. The angular correlations of the capture-gamma-ray cascade through the first excited state of C^{12} at 4.43 MeV were measured in the region of one resonance.

The $T=1$ levels of C^{12} and their transition strengths to the ground state have been calculated by Vinh-Mau and Brown[3] using the particle-hole formalism. More recently, Gillet and Vinh-Mau[4] and Goswami and Pal[5] have extended these calculations. In the present work nine distinct resonances were observed and, with varying degrees of completeness and certainty, information was obtained about the quantum numbers and partial widths of each compound-nucleus state so formed. Thus, it has been possible to assess the degree of validity of some of the predictions of the particle-hole calculations.

The experimental results for the various outgoing channels are described first. Then these results are discussed in terms of the compound-nucleus states, and finally the properties of these states are compared with the theoretical predictions.

II. EXPERIMENTAL RESULTS

1. $B^{11}(p,\gamma)C^{12}$, C^{12*}

A thin metallic boron target (usually depleted in B^{10}) deposited on a thick gold or tantalum backing was "wobbled" about a beam of protons accelerated in the Argonne 4.5-MeV Van de Graaff generator. Experimental details have been described previously.[6] Although targets of various thicknesses were used, the energy scale was obtained with a thin (15 keV at 1 MeV) evaporated target whose average thickness was determined by measuring the yield of gamma rays. Data were recorded at intervals varying from 10 to 100 keV.

The gamma rays were detected with a NaI(Tl)

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Present address: Stanford University, Stanford, California.
‡ Present address: U. S. Naval Research Laboratory, Washington, D. C.

[1] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).
[2] J. K. Bair, J. D. Kington, and H. B. Willard, Phys. Rev. **100**, 21 (1955).
[3] N. Vinh-Mau and G. E. Brown, Nucl. Phys. **29**, 89 (1962).
[4] V. Gillet and N. Vinh-Mau, Nucl. Phys. **54**, 321 (1964).
[5] A. Goswami and M. K. Pal, Nucl. Phys. **44**, 294 (1963).
[6] R. G. Allas, S. S. Hanna, L. Meyer-Schützmeister, and R. E. Segel, Nucl. Phys. **58**, 122 (1964).

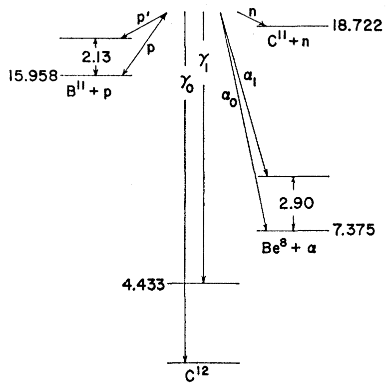

FIG. 1. Energy-level diagram showing the transitions that were studied in the present work.

crystal, 25 cm in diameter and 20 cm thick. The associated circuitry was conventional except that it included an anti-pileup circuit[6] which was especially helpful above the neutron threshold. The neutron-induced background was reduced by inserting about 45 cm of paraffin between the target and the crystal. A typical pulse-height spectrum is shown in Fig. 2. The high-energy portion of the spectrum contains the two capture gamma rays γ_0 and γ_1 which lead to the ground state and first excited state of C^{12} as well as a cosmic-ray background.

Data obtained at six angles ranging from 0 to 143° were fitted with series of Legendre polynomials

$$d\sigma/d\omega = A_0[1+\sum_{n=1}^{4} a_n P_n(\cos\theta)]. \quad (1)$$

The total cross section is $4\pi A_0$. The coefficients obtained for γ_0 are plotted in Fig. 3. The γ_0 yield is dominated by two resonances: one at $E_p = 1.42$ MeV that is about 1.25 MeV (lab) wide, and one (possibly complex) at about $E_p = 3.5$ MeV that is about 1.2 MeV (lab) wide. The angular-distribution coefficient a_4 is approximately zero everywhere, except perhaps near 3.0 MeV, while a_3 and a_1 are close to zero everywhere except near $E_p = 3.10$ MeV where both exhibit anomalies about 100 keV wide. The coefficient a_2 is small at both of the strong resonances but in between it is large and negative. Thus at 2.9 MeV the angular distribution is highly anisotropic and approximately of the form $W(\theta) = 1 - 0.7P_2$.

The Legendre polynomial coefficients extracted from the measurements on γ_1 are shown in Fig. 4. Resonances at $E_p = 0.65$ MeV [335 keV (lab) wide] and at $E_p = 3.11$ MeV [110 keV (lab) wide] appear in the total γ_1 cross section. However, unlike the situation for γ_0, the bulk of the γ_1 yield does not appear to be due to these distinct resonances. Above $E_p = 1$ MeV most of the yield seems to arise from broad, overlapping levels. The broad levels at $E_p = 1.4$ MeV and 3.5 MeV that dominate the γ_0 yield apparently are also present in the γ_1 yield, as is broad structure centered at about $E_p = 2.6$ MeV.

The complexity in the yield of γ_1 is evidenced by the behavior of the Legendre polynomial coefficients. The coefficient a_1, which can only be due to interference between levels of opposite parity, is often large (>0.2 in absolute value) and shows considerable variation with energy; only below $E_p = 1$ MeV is a_1 uniformly small. The coefficient a_2 is small (≈ 0.1) below $E_p = 1.5$ MeV; above this energy a_2 exhibits the same sort of

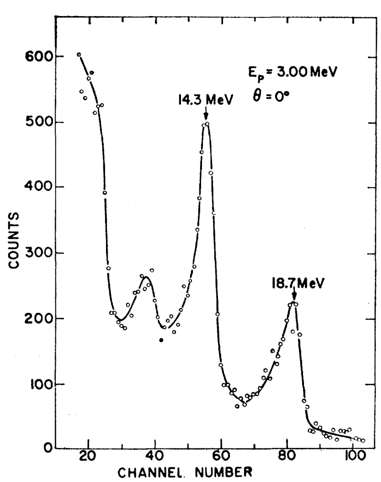

FIG. 2. Typical pulse-height spectrum from the NaI(Tl) crystal, 25 cm in diameter and 20 cm thick. The weak peak at about 11 MeV is due to the transition to the second excited state in C^{12} and/or to the ground-state gamma ray from the $B^{10}(p,\gamma)C^{11}$ reaction.

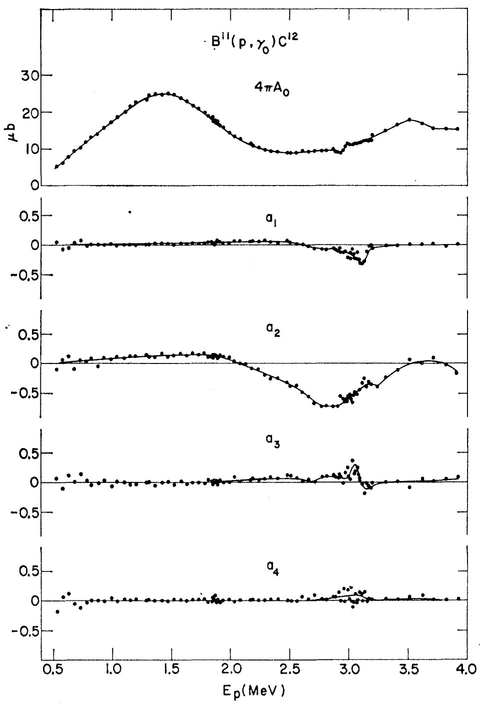

FIG. 3. Coefficients obtained in fitting series of Legendre polynomials to the angular distributions for $B^{11}(p,\gamma_0)C^{12}$.

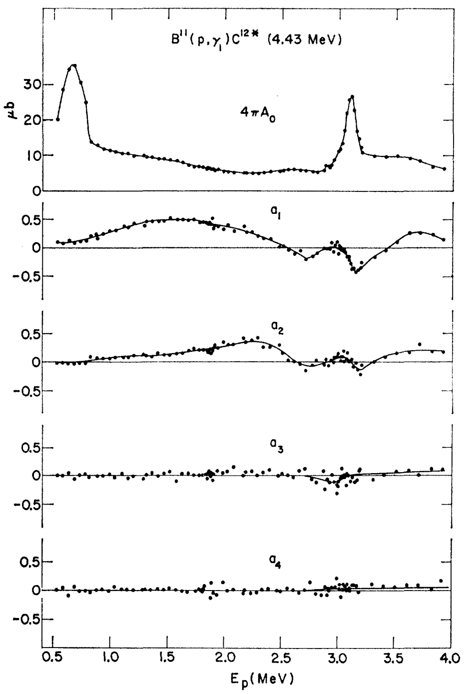

FIG. 4. Coefficients obtained in fitting series of Legendre polynomials to the angular distributions for $B^{11}(p,\gamma_1)C^{12}$.

broad structure as is present in the total γ_1 cross section The coefficients a_3 and a_4 are usually close to zero. Except at $E_p=3.1$ MeV, no obvious correlations exist between the variations in the angular-distribution coefficients and the structure in the total cross section.

The absolute cross sections were obtained from a measurement of the thick-target yield. In this measurement, the 90° yield integrated from $E_p=1$ to 2 MeV was determined by subtracting the yield at 1 MeV from that at 2 MeV. The efficiency of the crystal, defined as the number of counts in the "photopeak" per incident gamma ray, was calculated[7] to be about 55% for 14–18-MeV gamma rays for the particular experimental arrangement that was used. This thick-target measurement was combined with the measured energy dependence of the yield from a thin target and the known energy dependence of the stopping power in order to arrive at the absolute cross sections.

Huus and Day[8] have measured the 90° yield of gamma rays from $B^{11}(p,\gamma)$ for $E_p\leqslant 2.8$ MeV. Their gamma-ray spectra agree with those observed at 90° in the present work but their absolute cross sections are about 50% larger. Bair, Kington, and Willard[2] have reported yield curves for γ_0 and γ_1 at 0 and 90° for $2.0\leqslant E_p\leqslant 5.4$ MeV, but give only relative cross sections. The energy dependence of their curves agrees with the present data but their ratio of the intensity of γ_1 to that of γ_0 is about double the present value. Gove and Paul[9] have measured a few angular distributions below $E_p=3$ MeV. For γ_0 they find that a_1 is positive and increases from about 0.03 at 1.1 MeV to about 0.1 at 2.6 MeV; this result is close to the present observation that a_1 is indistinguishable from zero below 1.4 MeV and then rises monotonically to about 0.08 at 2.4 MeV. Gove and Paul find that a_2 (for γ_0) is constant at a value of about $+0.17$ over the resonance at $E_p=1.4$ MeV, but that it becomes negative above the resonance. Again this result is consistent with the present observation that a_2 rises from about $+0.10$ to about $+0.16$ over the resonance and then becomes negative. For γ_1 there is also general agreement in spite of some differences in detail; the earlier work indicates anomalies at about 1.4 and 2.2 MeV in both a_1 and a_2, while the present data, which were taken in much finer energy steps, do not show such distinct structure.

The radiative capture of protons by B^{11} has been studied[6] extensively over the energy region 4 MeV$\leqslant E_p\leqslant$14 MeV in a manner similar to that reported here. In this higher region, the yields of γ_0 and γ_1 exhibit roughly giant-resonance shapes with some superimposed structure. The γ_0 giant resonance is centered at an excitation energy of 22.5 MeV, while the γ_1 giant resonance is centered at 26 MeV. Thus, the fact that the yield of γ_0 is about twice that of γ_1 in the region studied here might be due to the closer proximity of the γ_0 giant resonance. Except for an interference term that increases with increasing energy and is negligible at 4 MeV, the angular distribution of each gamma ray is approximately constant through the giant-resonance

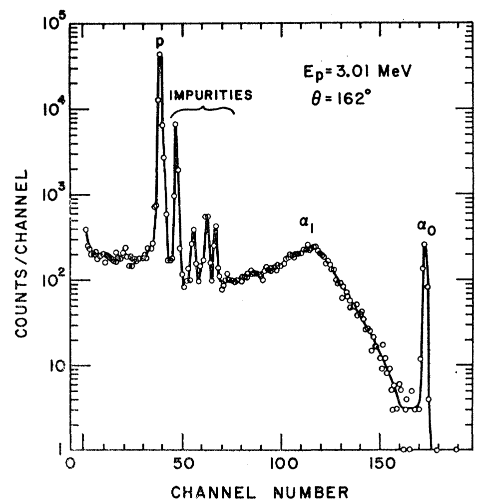

FIG. 5. Charged-particle spectrum resulting from the interaction of B^{11} with 3.01-MeV protons. This spectrum was observed with a silicon detector.

[7] This calculation was performed by W. J. Snow using the program described by W. F. Miller, J. Reynolds, and W. J. Snow in the Argonne National Laboratory Report No. ANL-5902, 1958 (unpublished).

[8] T. Huus and R. B. Day, Phys. Rev. 91, 599 (1953).

[9] H. E. Gove and E. B. Paul, Phys. Rev. 97, 104 (1955).

region. For γ_0 the characteristic angular distribution is $1-0.6P_2$ and for γ_1 it is isotropic. The similarity of the γ_0 angular distribution in the region between the 1.4-MeV and the 3.6-MeV resonances to that observed on the giant resonance appears to confirm that the γ_0 giant resonance influences this region. On the other hand, the greater distance to the γ_1 giant resonance, combined with the fact that more nearby levels contribute to γ_1, apparently obscures the effect of the γ_1 giant resonance on the region studied here.

The coefficient a_1, which must be due to the interference between radiations of opposite parity, has markedly different behavior for γ_0 and γ_1. Its value is usually close to zero (<0.1) for γ_0 but is usually much larger for γ_1. The γ_1 yield is so large that the negative-parity radiation is most probably E_1, while the smallness of a_3 for γ_1 suggests that the positive-parity radiation is $M1$ rather than $E2$. For γ_0, the $M1$ strength is known[3] to be concentrated in the level at 15.11 MeV and there is therefore little left at other energies to interfere with the dominant E_1 radiation.

2. $B^{11}(p,\alpha)Be^8$, Be^{8*}

Unbacked metallic B^{11} targets approximately 100 $\mu g/cm^2$ thick were bombarded with protons, and the emergent charged particles were observed with silicon detectors. A typical spectrum is given in Fig. 5. At the high-energy end of the spectrum there are the two alpha-particle groups, α_0 and α_1, which form the sharp sharp ground state and broad first excited state of Be^8, respectively. Intense groups of protons, elastically scattered by the target and its contaminants, appear at the low-energy end of the spectrum; these groups are discussed in the section on proton scattering. Two runs were made: one, in which the protons were biased out, covered the region from $E_p=1$ to 4 MeV, and the other, in which the protons were counted, covered the range from 0.55 to 4 MeV with special emphasis on the region below 1 MeV and on the regions near resonances. The angular distributions of alpha particles below $E_p=1$ MeV are somewhat less accurate than those above this energy because the large number of scattered protons in the low-energy region caused some pulse pileup in the detection system. A continuum of alpha particles from the breakup of Be^8 underlies most of the spectrum. In determining the intensity of α_1, a fairly narrow pulse-height region (≈ 1.5 MeV wide) was used and any contribution from the continuum was ignored. The spectra showed that any such contributions were small and would not have materially affected the conclusions that were drawn from the analysis.

Measurements were obtained at six angles ranging from 30° to 162°(lab). The intensities of α_0 and α_1 were determined by adding up appropriate channels and making corrections for solid angle, analyzer dead time, etc. The results were then expressed in a series of Legendre polynomials [Eq. (1)]. This analysis was done

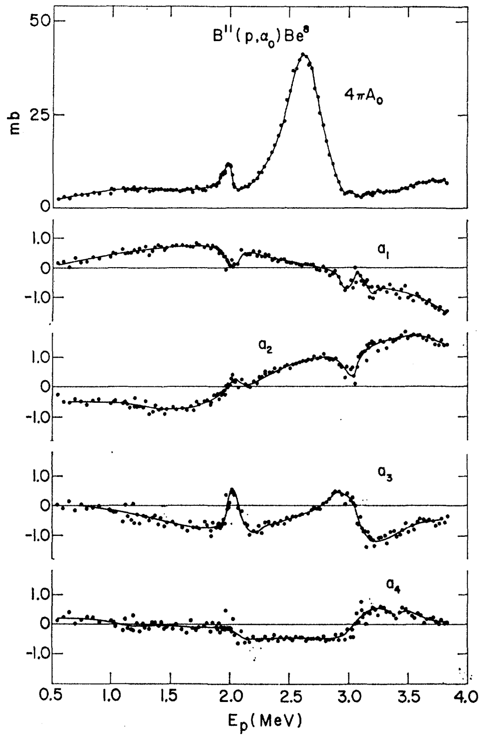

FIG. 6. Coefficients obtained in fitting series of Legendre polynomials to the angular distributions for $B^{11}(p,\alpha_0)Be^8$. The observed deviation from zero in a_4 below 1 MeV may not be significant because of the uncertainties in the data in this energy region.

with the aid of a computer program which first converted the data to the center-of-mass system and then determined the Legendre coefficients through a least-squares fitting procedure. The absolute cross sections were determined by measuring the ratio of intensities of alpha particles to gamma rays at one proton energy and using the absolute gamma-ray cross section derived from the thick-target-yield measurement described above.

Figure 6 shows the Legendre coefficients for α_0. The total yield has the appearance of being dominated by a single strong resonance, 340 keV (lab) wide and centered at $E_p=2.62$ MeV. A weaker, narrow resonance 100 keV (lab) wide is observed at 1.98 MeV and there is broad structure centered at about 3.7 MeV. The entire pattern is apparently superimposed on a continuum. All of the angular-distribution coefficients attain large values and exhibit complex behavior indicating that the level structure is not a simple one that can be described in terms of a few well-defined states. Some specific features of the angular distributions of α_0 are the following.

(1) The angular distributions tend to the approximate form $(1-0.4P_2)$ as the yield tends to zero at low energies. It is not clear what state in C^{12} is causing this deviation from the expected isotropy; the well-known 2^+ state[1] at 16.11 MeV ($E_p=0.163$ MeV) could

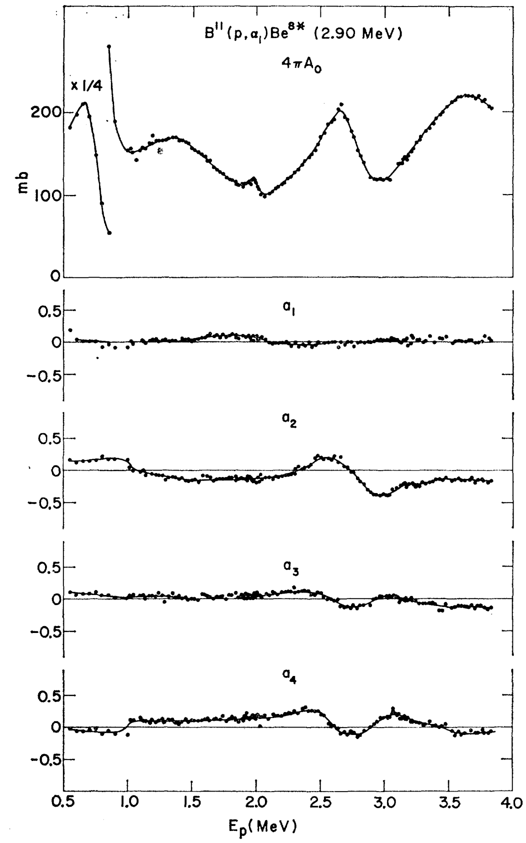

FIG. 7. Coefficients obtained in fitting series of Legendre polynomials to the angular distributions for $B^{11}(p,\alpha_1)Be^8$. The small deviations from zero in the a's below 1 MeV cannot be considered significant.

at most make only a 1% contribution to the yield of α_0 in the region 0.5 MeV$<E_p<$1.0 MeV.

(2) The resonance at $E_p=1.98$ MeV shows up clearly in the behavior of the coefficients a_1 and a_3 and possibly a_2.

(3) Both a_1 and a_2, and possibly a_3, show a narrow ($\Gamma\approx120$ keV) anomaly at $E_p\approx3.01$ MeV. The total yield curve also suggests a state at this energy but this evidence cannot be considered as definitive. The other exit channels appear to be unaffected by any state at this energy, although possible disturbances are present in the odd Legendre terms in the γ_1 angular distributions.

(4) The coefficient a_1 shows an anomaly whose position and width appear to correspond to the resonance in the γ_1 yield at $E_p=3.11$ MeV.

Figure 7 shows the Legendre coefficients for α_1. The α_1 yield is about 10 times the α_0 yield, and resonances in the total yield appear at $E_p=0.65$ MeV ($\Gamma_{lab}=300$ keV), 1.35 MeV [$\Gamma_{lab}\approx1$MeV), 1.98 MeV ($\Gamma_{lab}=90$ keV), 2.65 MeV ($\Gamma_{lab}=300$ keV), and 3.7 MeV ($\Gamma_{lab}\approx1$ MeV). At each of these energies, similar structure is seen at least one other exit channel. The angular distributions are much more constant for α_1 than they are for α_0, the odd terms for α_1 being particularly small. No narrow structure is present in any of the coefficients for α_1. It appears that usually so many levels are contributing to the α_1 yield that the angular distributions represent a roughly isotropic average, although at the lowest energies the resonance at $E_p=0.65$ MeV undoubtedly dominates and the near isotropy observed there is probably due to s-wave formation.

Recently a study of the reaction $B^{11}(p,\alpha)Be^8$ from $E_p=3.5$ to 13 MeV has been reported by Blieden.[10] In the region of overlap, there is good agreement with the present work. From Blieden's work it appears that at higher energies the α_0 angular distributions continue to be less isotropic and more complex than the α_1 angular distributions.

An extensive study of the reaction $B^{11}(p,\alpha)Be^8$ from $E_p=0.7$ to 6.0 MeV has been published by Symons and Treacy.[11] These authors made measurements at more angles (eight and sometimes thirteen angles instead of six) than in the present work but at fewer energies (29 energies for α_0 and five for α_1 between 0.5 and 4 MeV, as compared with 132 for each α group in the present work). Symons and Treacy found that terms higher than P_4 were not needed in fitting the data and therefore observations made at many angles serve chiefly to increase the accuracy in determining the coefficients. They also show yield curves at fixed angles, measured in small energy steps.

The present results are everywhere consistent with the angular distributions and yield curves of Symons and Treacy. Their Legendre coefficients, which they give in tabular form, would show excellent agreement if plotted on the curves of Figs. 6 and 7. Because of the coarser spacing between their points, the narrow anomalies in the Legendre coefficients for α_0 at $E_p\approx2.0$ and 3.0 MeV are not as apparent in their work, although their total yield curve for α_0 clearly shows the resonance at $E_p=1.98$ MeV. Also, Symons and Treacy plot $A_n=A_0a_n$ rather than a_n, so the anomaly at $E_p=3.01$ MeV is suppressed in their curves. They indicate that the resonance at $E_p=1.98$ MeV shows up only in the total α_0 yield but not in the coefficients A_n for $n>0$. However, when a large number of points is obtained in the vicinity of this resonance, the structure in the Legendre coefficients stands out clearly (Fig. 6).

There is fair agreement in the absolute cross sections in the two investigations. For α_0, the cross section given by Symons and Treacy is about 1.4 times the value found in the present work at 1 MeV, and this factor decreases to 1.1 at 4 MeV. For α_1, the factor is constant at about 1.4. Beckman, Huus, and Zupančič[12] have measured the α-particle yields at 90° for 0.3 MeV$\leqslant E_p\leqslant$1.8 MeV and list absolute cross sections at 0.67 and

[10] H. R. Blieden, Bull. Am. Phys. Soc. **9**, 171 (1964); and private communication.
[11] G. D. Symons and P. B. Treacy, Nucl. Phys. **46**, 93 (1963).
[12] O. Beckman, T. Huus, and Č. Zupančič, Phys. Rev. **91**, 606 (1953).

1.4 MeV which, after correcting for the angular distributions, are about 0.8 of those found here.

3. Angular Correlation in $B^{11}(p,\gamma\gamma)C^{12}$

Angular correlations were measured at the resonance at $E_p=3.11$ MeV. The resonance appears to be well enough isolated so that angular-correlation measurements could be helpful in making a spin assignment. In the angular distribution for γ_1 (the first gamma ray of the cascade) it is mainly the isotropic term that is resonant. This indicates that the capturing state is practically unoriented and simplifies the interpretation of the angular correlation. The absence of a detectable resonance in the alpha-particle yield indicates an assignment of $T=1$ to the resonance, while the strength of the γ_1 yield requires a dipole transition; the change in isotopic spin renders it unlikely that the transition is an enhanced $E2$. The radiation γ_1, therefore, appears to be an isotopic-spin-allowed dipole transition and it is unlikely that a quadrupole admixture would be strong enough to affect the correlation substantially.

The correlations calculated for an unoriented capturing state and for pure dipole radiation for γ_1 are shown in Table I. Under these assumptions the correlation is

TABLE I. Calculated γ-γ angular correlations for the cascade $J(1)2(2)0$.

J	$W(\theta)$	$W(180)/W(90)$
1	$1-\frac{1}{4}P_2(\cos\theta)$	0.667
2	$1+\frac{1}{4}P_2(\cos\theta)$	1.429
3	$1-(1/14)P_2(\cos\theta)$	0.897

$W(\theta)=1+a_2P_2(\cos\theta)$ and it is completely determined by measuring coincidences between the γ rays emitted at any two angles that are not symmetrical about 90°, the pair of angles yielding the greatest sensitivity being 90° and 180°. The second gamma ray (4.43 MeV) was detected with a fixed NaI(Tl) crystal, 10 cm in diameter by 10 cm thick, while the primary gamma ray γ_1 was detected with the large NaI(Tl) crystal, 25 cm in diameter by 20 cm thick, which could be rotated. The ratio $W(180)/W(90)$ was measured on the 3.11-MeV resonance at different angles for the fixed counter and also for different energies over the resonance. The results are summarized in Table II. The following conclusions can be drawn from the measurements.

(1) Since the triple correlation does not vary appreciably with the angle of the fixed counter, the assumption that the resonant state is unoriented is confirmed.

(2) The monotonic variation of the correlation over the resonance indicates interference between the resonance and the nonresonant background.

(3) The measured value of the correlation on resonance indicates a spin of 2 for the capturing state at $E_x=18.83$ MeV.

TABLE II. Measured values of the asymmetry $W(180)/W(90)$ for the γ-γ angular correlation at the resonance at $E_p=3.11$ MeV. The gamma-ray cascade proceeds through the first excited state of C^{12}. In some cases it was more convenient to make the measurement at 165° instead of 180°, in which case an appropriate correction has been applied. The 4.43-MeV gamma ray of the cascade was detected by the fixed counter whose angle is given relative to the beam direction.

E_p	θ_{fixed}	$W(180)/W(90)$
3.11	44°	1.44±0.10
3.11	135°	1.50±0.11
3.11	90°	1.62±0.12
3.16	90°	2.32±0.27
3.07	90°	1.13±0.10

4. $B^{11}(p,n)C^{11}$

The threshold for the reaction $B^{11}(p,n)C^{11}$ is at $E_p=3.02$ MeV. For bombarding energies below 5.19 MeV the only neutron channel open is that leading directly to the ground state of C^{11}. The total (p,n) cross section was measured in about 10-keV steps from threshold to 3.8 MeV by bombarding a rotating[6] B^{11} target for a few minutes, until a fixed charge was accumulated, and then observing the resultant C^{11} activity. The decay was followed for 20 min and then the procedure was repeated at the next higher energy. Since extraneous background was negligibly small, the yield at each energy could easily be computed by correcting for the activity remaining from previous bombardments. The absolute cross section was determined by measuring the thick-target yield at a bombarding energy of 3.5 MeV.

The yield curve for $B^{11}(p,n)C^{11}$ obtained in this way (Fig. 8) is characterized by a broad maximum at $E_p\approx3.65$ MeV and a much sharper anomaly at about 3.12 MeV. This sharper structure can be identified with the 3.11-MeV resonance in the (p,γ) yield. The closeness of this resonance to the neutron threshold greatly distorts the yield curve because of the rapidly increasing neutron penetrability. The broad maximum at 3.65 MeV coincides approximately with maxima in the α_0, α_1, γ_0, and γ_1 yield curves.

These resonances agree with those reported by Bair *et al.*[2] and by Gibbons and Macklin.[13] In the former

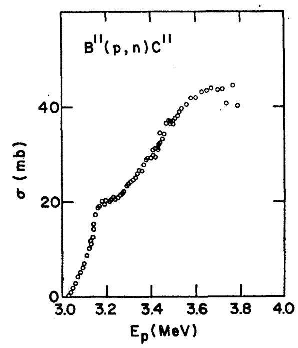

FIG. 8. Yield of C^{11} from $B^{11}(p,n)C^{11}$. In the energy range studied, only the ground-state neutron is energetically possible.

[13] J. H. Gibbons and R. L. Macklin, Phys. Rev. **114**, 571 (1959).

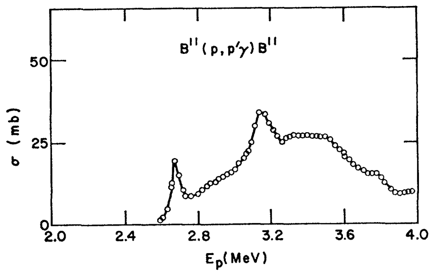

FIG. 9. Yield of the 2.13-MeV gamma ray from the first excited state in B^{11}. The energy dependence of the yield is from Ref. 2 and the absolute scale from the present work.

investigation the neutron yield in the forward direction was measured; in the latter the total cross section was determined. Blaser, Boehm, Marmier, and Scherrer[14] measured the residual C^{11} activity in this energy region but with coarser energy steps than in the present work. At the 3.6-MeV resonance they report a cross section of 56.5 mb, which is about 25% greater than that found here.

5. $B^{11}(p,p')B^{11*}$

The yield curve of the 2.13-MeV gamma ray from the first excited state of B^{11} has been reported by Bair *et al.*[2] Since[1] the spin of this state is $\frac{1}{2}$, the gamma rays must be emitted isotropically and therefore angular distributions were not measured (except to check the symmetry of the apparatus). Bair *et al.* report only relative cross sections and therefore we have completed the measurements on this outgoing channel by determining the absolute cross section. This was done by measuring the thick-target yield of the 2.13-MeV gamma ray at $E_p=3$ MeV. Figure 9 shows the yield curve of this gamma ray. The well defined peaks seen at $E_p=2.66$ MeV ($\Gamma=46$ keV) and at 3.15 MeV ($\Gamma=100$ keV) are superimposed upon broad structure that is centered at about 3.4 MeV. Even after allowing for the distortion due to the proximity of the (p,p') threshold, the resonance at $E_p=2.66$ MeV is much too narrow to be identified with the resonance at 2.62 MeV observed in the (p,α_0) reaction (Fig. 6). The resonance at 3.15 MeV is comparable in position and width to that observed at 3.11 MeV in $B^{11}(p,\gamma)$. Broad structure centered at about 3.5 MeV is observed in all of the exit channels. For the inelastic scattering, as well as for some of the other channels, the structure in the 3.5-MeV energy region seems to indicate the presence of more than one level.

6. $B^{11}(p,p)B^{11}$

Useful data were obtained at five angles. At the sixth angle, the most forward one at 30° (lab), the Coulomb scattering from the heavy contaminants overwhelmed the scattering from B^{11}. The elastic-scattering cross sections as a function of energy at two of the angles, 94.8° and 163.1° (c.m.), are shown in Fig. 10. The absolute cross sections were obtained in the same way as for the (p,α) reactions, i.e., they were based on a measurement of a thick-target (p,γ) yield. At all angles the scattering from the contaminants dominated at the lowest bombarding energies and, therefore, data are plotted only where a reasonably accurate determination of the intensity of the $B^{11}(p,p)B^{11}$ reaction could be made. Narrow anomalies are present at $E_p=1.98$ and 3.11 MeV. Both of these anomalies are positive at the three forward angles (64.1°, 94.8°, and 109.6°), absent at 128.9°, and negative at 163.1° (all angles in the c.m. system). The broad resonance at $E_p=2.6$ MeV has the typical resonance shape at the backward angles, but at the three forward angles it appears more like an interference effect.

Symons and Treacy[11] have measured the elastic scattering between $E_p=2.4$ MeV and 3.1 MeV at the c.m. angle of 157.2°. The present result at 163.1° agrees in shape and absolute cross section with their measurement. Tautfest and Rubin[15] have measured the elastic scattering at 152.6° between $E_p=0.58$ MeV and 2.0 MeV with results similar to those obtained here in the region of overlap. However, Tautfest and Rubin do not observe the anomaly at $E_p=1.98$ MeV. This apparent discrepancy is less serious if it is noted that the anomaly is much less obvious if the curve ends at 2.0 MeV and that the anomaly is probably smaller at 152.6° than it is at 163.1°.

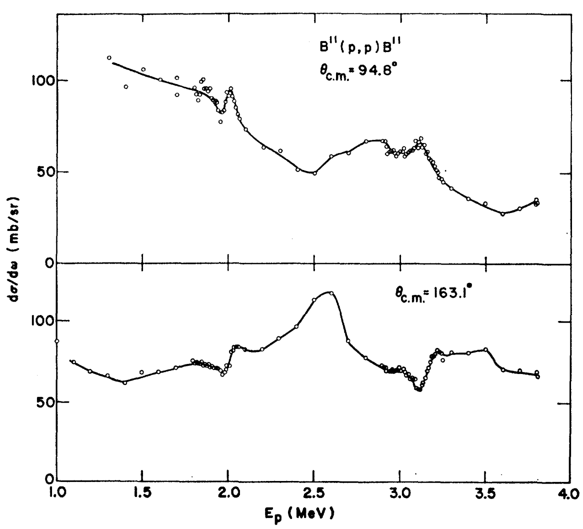

FIG. 10. Elastic-scattering yield curves. At energies less than those for which the yield has been plotted, the scattering from the contaminants precluded an accurate determination of the yield of the scattering from the boron.

[14] J. P. Blaser, F. Boehm, P. Marmier, and P. Scherrer, Helv. Phys. Acta **24**, 465 (1951).

[15] G. W. Tautfest and S. Rubin, Phys. Rev. **103**, 196 (1956).

TABLE III. Resonance parameters for the levels observed in the present experiment. The widths are given in the c.m. system. Dots indicate that an exit channel is not energetically possible; a blank indicates that the quantity was not determined. A quantity in parentheses is especially doubtful. The notation n.p. designates natural parity.

E_p (MeV)	C^{12*} (MeV)	Γ (MeV)	Γ_p (MeV)	$\Gamma_{p'}$ (keV)	Γ_n (keV)	Γ_{α_0} (keV)	Γ_{α_1} (keV)	Γ_{γ_0} (eV)	Γ_{γ_1} (eV)	J^π	T	References to previous work
0.65	16.56	0.30	0.15	···	···	<0.27	150	<0.4	8.0	2^-	(1)	8, 9, 12, 15, 16, 17
1.42	17.26	1.15	1.0	···	···	10	140	44	5	1^-	1	8, 9, 12, 16
1.98	17.77	0.092	0.076	···	···	4.6	11.4	<0.5	<0.5	0^+	1	11, 17
2.62	18.36	0.31	0.068	<1.5	···	65	177	<1.5	3.2	3^-	(0)	9, 11, 16
2.66	18.40	0.042	0.033	9	···	<1	<5	<0.5	<0.5	0^-		2
3.01	18.72	0.10	<0.01		···					n.p.	(1)	
3.11	18.81	0.10	0.097	2.0	1.1	<0.2	<1.5	(0.4)	2.0	2^+	1	2
3.5	19.2	1.1	0.30	400	150	50	200	25	10	1^-	1	2, 11
3.7	19.4	1.1	0.45	50	100	20	450	<3	3	2^+	0	11

Dearnaley, Dissanaike, French, and Jones[16] have measured the proton scattering from B^{11} below 1 MeV. In the region of overlap (i.e., at backward angles near 1 MeV) the cross sections of Dearnaley *et al.* are about 1.5 times those reported here. (We note that the cross sections of Dearnaley *et al.* are also 1.5 to 2 times those of Tautfest and Rubin.)

III. EXCITED STATES OF C^{12}

1. State at $E_x=16.56$ MeV, $E_p=0.65$ MeV

The large (p,α_1) cross section at this resonance requires that $\Gamma_p\Gamma_{\alpha_1}/\Gamma^2$ be close to its maximum value of $\frac{1}{4}$, in which case $\Gamma_p\approx150$ keV. At this low energy, such a large width is possible only for s-wave protons and, therefore, the compound state must be either 1^- or 2^-. The near isotropy of the two resonant exit channels, α_1 and γ_1, supports the contention of s-wave formation. The size of the (p,α_1) cross section indicates that $(2J+1)\geqslant5$ so that only the 2^- can be correct. This assignment is consistent with the absence of observable resonances in the yields of α_0 and γ_0. Dearnaley *et al.*[16] also obtained an assignment of 2^- on the basis of their proton-scattering observations, and this assignment is in agreement with earlier experiments.[8,9,12,15,17] The reduced width for α_1 is $\theta_{\alpha_1}{}^2\approx0.05$ which, although typical for an allowed alpha transition from a normal nuclues, is probably small for the "3-alpha" nucleus C^{12}. The $E1$ gamma ray γ_1 has a reduced matrix element $|M|^2\approx0.01$ Weisskopf units, a value rather typical of an isotopic-spin-allowed transition.[18,19] Thus, the α_1 and γ_1 decays seem to favor $T=1$ for this state, although this assignment cannot be considered definitive. Other investigators have come to the same conclusion from substantially the same evidence. The partial widths determined here for the various exit channels from this state are in satisfactory agreement with the previously accepted values.[1] The resonance parameters obtained for the various resonances are summarized in Table III.

2. State at $E_x=17.26$ MeV, $E_p=1.42$ MeV

For this state $(2J+1)\Gamma_{\gamma_0}\geqslant115$ eV. This indicates an assignment of 1^- with $T=1$ most probable. This assignment has been reached by most of the previous investigators.[8,9,12,16,17] While α_1 is clearly resonant, the resonant cross section cannot be accurately determined because the resonance is not well isolated; it can be estimated that $\sigma_0(\alpha_1)\approx80\times10^{-27}$ cm^2. Although the resonance is so broad that it is difficult to assess its strength in the weakly resonant channels of α_0 and γ_1, it appears to have a measurable effect in both of these exit channels. We estimate $\sigma_0(\alpha_0)\approx5\times1^{-27}$ cm^2 and $\sigma_0(\gamma_1)\approx3\times10^{-30}$ cm^2. The various nonelastic resonant cross sections permit two solutions: $\Gamma_p=1.0$ MeV, $\Gamma_{\alpha_1}=140$ keV, $\Gamma_{\alpha_0}=10$ keV, $\Gamma_{\gamma_1}=5$ eV, $\Gamma_{\gamma_0}=44$ eV; and $\Gamma_p=150$ keV, $\Gamma_{\alpha_1}=940$ keV, $\Gamma_{\alpha_0}=60$ keV, $\Gamma_{\gamma_1}=35$ eV, $\Gamma_{\gamma_0}=290$ eV. The former solution predicts a resonant proton-scattering cross section $\sigma_0(p)\approx0.05\times10^{-24}$ cm^2/sr while the latter predicts $\sigma_0(p)\approx0.001\times10^{-24}$ cm^2/sr. (Unless stated otherwise, the differential scattering cross section is estimated as the calculated total resonant scattering cross section divided by 4π.) It is particularly difficult to isolate the resonant scattering for the proton because, in addition to the presence of the tails of nearby resonances, Coulomb and "hard-sphere" scattering are present. A complete analysis of the proton scattering is beyond the quality of the present data and the scope of the present work. However, it is noteworthy that the incoherent sum of the Coulomb scattering (≈0.03 b/sr at 120°) and the hard-sphere scattering (≈0.01 b/sr) is much smaller than the observed cross section at backward angles. It appears, therefore, that there is a substantial resonant contribution in this energy region and this favors the solution for which the proton width is dominant. On the other hand, in the analysis of their data below 1 MeV, Dearnaley *et al.*[16] favor the solution in which α_1 contributes most of the width. While the

[16] G. Dearnaley, G. A. Dissanaike, A. P. French, and G. L. Jones, Phys. Rev. **108**, 743 (1957).

[17] E. B. Paul and R. L. Clarke, Phys. Rev. **91**, 463 (1953).

[18] D. H. Wilkinson, *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, pp. 852–889.

[19] E. K. Warburton, Natl. Acad. Sci.–Natl. Res. Council Publ. **974**, pp. 180–204.

proton-scattering data and the analysis of Dearnaley *et al.* are much more detailed than those in the present work their observations were confined to the energy region below $E_p = 1$ MeV where the resonance at 1.4 MeV has relatively little effect.

The recent gamma-ray absorption measurements of Wyckoff, Ziegler, Koch, and Uhlig[20] probably settle this issue. In a gamma-ray absorption experiment the measured quality $\int \sigma_{abs} dE$ depends directly on Γ_{γ_0}. The value of Γ_{γ_0} derived from the data of Wyckoff *et al.* is 62 eV, which is consistent only with the solution with the larger proton width. However, we note that a second recent absorption measurement[21] leads to a substantially greater value of Γ_{γ_0}. The solution with the larger proton width is the more satisfying theoretically, since the other solution has a large alpha width which implies $T=0$ and at the same time a large gamma width which indicates the opposite assignment of $T=1$. Combining all of the evidence, we adopt the solution with the larger proton width.

3. State at $E_x = 17.77$ MeV, $E_p = 1.98$ MeV

The measurements of the (p,α) cross section lead to two solutions which give a resonant proton cross section of approximately $(2J+1)\times 10^{-27}$ cm^2/sr or approximately $[0.3/(2J+1)]\times 10^{-27}$ cm^2/sr. Since the anomaly in the proton scattering at this energy is approximately 15×10^{-27} cm^2/sr, the solution with the larger proton width is favored. Symons and Treacy[11] favor the other solution, basing their preferences on the failure of Tautfest and Rubin[15] to observe a proton scattering anomaly at this energy. However, as discussed above in the section on proton scattering, the failure of Tautfest and Rubin to observe the anomaly is understandable and the presence of this resonance in the proton scattering is unambiguous in the present work. Using the solution with the larger proton width, we find that the alpha widths (in keV) are $\Gamma_{\alpha_0} \approx 4.0/(2J+1)$ and $\Gamma_{\alpha_1} \approx 10.0/(2J+1)$. Taking 10^{-30} cm^2 as the upper limit for the cross section for the production of either γ_0 or γ_1, we find that $(2J+1)\Gamma_\gamma < 0.5$ eV for both γ_0 and γ_1.

The emission of α_0 from this resonance indicates that the state has natural parity (i.e., it has an assignment of 0^+, 1^-, 2^+, 3^-, etc.). A spin of $J \geqslant 4$ and natural parity requires formation by protons with $l \geqslant 3$, which is not consistent with the large proton width. The small alpha-particle widths indicate $T=1$. A 3^- assignment would require *d*-wave formation and is unlikely because the proton width would be approximately five times a single-particle width. In addition, no mixture of channel spins would give both $a_2 \approx 0$ and $a_4 \approx 0$ in the angular distribution for α_0, as required by the experimental data which do not show large anomalies in the even Legendre polynomials. Furthermore, a 3^-, $T=1$ state would indicate an isotopic-spin-allowed $E1$ transition for γ_1, in which case its small width, $|M|^2 \leqslant 5\times 10^{-4}$ Weisskopf units, would be very surprising.[18,19] Thus, 3^- cannot be considered an acceptable assignment. Similarity, 1^- is improbable because in this case both γ_0 and γ_1 would have to be very strongly inhibited.

It is more difficult to choose between the two positive-parity assignments, 0^+ and 2^+. However, the size of the resonance in the proton scattering is considerably smaller than expected if $J=2$. The failure to observe the γ_1 transition, which for a 2^+ compound state would represent an isotopic-spin-allowed $M1$ transition with $|M|^2 < 0.01$, also militates against the 2^+ assignment. The choice 0^+ is consistent with all of the data. The P_3 term in the angular distribution for α_0 would then be due to interference with a 3^- state. As is shown below, the next higher known state ($E_p = 2.62$ MeV, $\Gamma_{lab} = 340$ keV) is indeed probably 3^-. In the yield curve for α_0, it appears that the resonance at 2.62 MeV is still quite influential at $E_p = 1.98$ MeV so that interference between these two resonances is probable. The absence of the gamma rays γ_0 and γ_1 and the strength of the resonance in elastic scattering all follow naturally from a 0^+ assignment.

Symons and Treacy[11] assigned 0^+ to this state because of "the absence . . . of any pronounced peak in A_L for $L>0$" in the alpha-particle reactions. Although the present work reveals structure in the energy dependence of these coefficients, the 0^+ assignment remains the most probable one.

Finally, we note that although the cross sections of the present work are in satisfactory agreement with those of Symons and Treacy, the derived partial widths at this resonance are in disagreement. This discrepancy has been traced to an error in the computation of Symons and Treacy.[22]

4. State at $E_x = 18.36$ MeV, $E_p = 2.62$ MeV

The resonance in the yield of α_0 requires natural parity, and the presence of a large P_4 term in the angular distribution requires $J \geqslant 2$ and $l_p \geqslant 2$. Because of these requirements, we favor an assignment of 3^-. Again, the (p,α) cross sections give two solutions for the partial widths: $\Gamma_p = 68$ or 242 keV. The small barrier penetrability (≈ 0.03) for *d* waves is compatible only with the smaller proton width. This solution predicts a proton-scattering resonance with a peak cross section of ≈ 3.5 mb/sr. While the data exhibit anomalies which are several times as large as this at some angles, the anomalies have the appearance of being mainly due to interference effects which could, of course, be much larger than the scattering from the resonance itself. For an assignment of 3^-, the gamma ray γ_1 is $E1$ with a reduced width $|M|^2 \approx 2\times 10^{-3}$ Weisskopf units. Such a small width favors an assignment of $T=0$ for the state,

[20] J. M. Wyckoff, B. Ziegler, H. W. Koch, and R. Uhlig, Phys. Rev. **137**, B576 (1965).

[21] N. A. Burgov, G. V. Danilyan, B. S. Dolbilkin, L. E. Lazareva, and F. A. Nikolaev, quoted in Ref. 20.

[22] P. B. Treacy (private communication).

although the alpha-particle widths cast some doubt on this assignment. As noted above, the 3^- assignment explains the anomaly in the coefficient a_3 in the angular distribution of α_0 at the 1.98-MeV resonance.

Although the present experimental data are in satisfactory agreement with those of Symons and Treacy the latter favor an assignment of 2^+ for the resonance. The latter authors attribute the P_4 term in the angular-distribution of α_0 to an interference between the p waves and a 4% f wave component in the incident protons. They reject the assignment of 3^- on the basis that a pure 3^- state cannot accurately reproduce the α_0 angular distribution. However, the prominence of the interference terms in P_1 and P_3 indicates that other levels are contributing to the yield. Moreover, a 4% f-wave contribution would require an f-wave reduced width some four times the single-particle limit and this appears unreasonable. Finally, we note that the same discrepancy in the calculated partial widths that is cited in the discussion of the 1.98-MeV resonance is also present for this resonance.

Gove and Paul[9] tentatively assigned 2^+ to this state, primarily on the basis of the γ_0 angular distribution at 2.6 MeV. However, the present work shows that the 2.62-MeV resonance makes at most a minor contribution to the γ_0 yield at this energy.

5. State at $E_x = 18.40$ MeV, $E_p = 2.66$ MeV

The strength of this resonance in the inelastic proton channel[2] combined with the low energy of the outgoing protons indicates that $l=0$ for these protons. Also, of the two possible solutions for Γ_p and Γ_p' the one with the smaller inelastic proton width should be chosen. The failure to observe an anomaly in the elastic scattering can be attributed to the wide spacing (50 keV) between the data points, the expected strong interference from the broad 2.62-MeV resonance, and the probable smallness ($\approx 6\times 10^{-27}$ cm^2/sr) of the anomaly. For s-wave inelastic protons, the assignment of the resonance is limited to 0^- or 1^-. For a 1^- state, either the observed alpha or gamma width would be unreasonably small, depending on whether $T=0$ or 1. Furthermore, if a 1^- state were formed by incident s waves, then the observed proton width would be unreasonably small; but a 0^- state would be formed by d waves, for which the observed width is quite reasonable. For a 0^- state the emission of α_0, α_1, and γ_0 is strictly forbidden, while γ_1 would correspond to an $M2$ transition and would be correspondingly weak. Thus, 0^- appears to be the assignment that is most consistent with all of the data. Since all of the exit channels sensitive to isotopic spin are closed, the isotopic spin of the state cannot be determined.

6. State at $E_x = 18.72$ MeV, $E_p = 3.01$ MeV

The only firm evidence for an anomaly at this energy is in the angular distributions for α_0, but in these distributions it is well established. It occurs in the energy dependence of at least two of the Legendre coefficients, where it was observed in two independent runs. It is also evident in the work of Symons and Treacy.[11] The small cross sections for all channels suggest a small proton width. The small alpha-particle widths suggest $T=1$ and the anomalies in the α_0 channel require natural parity.

7. State at $E_x = 18.81$ MeV, $E_p = 3.11$ MeV

The anomalies in the coefficients a_1 and a_3 in the angular distributions for γ_0 indicate that γ_0 is primarily $E2$ radiation interfering with the background radiation (which is predominantly $E1$). Thus 2^+ is the indicated assignment. This assignment is supported by the angular-correlation measurements which select $J=2$ and by the anomaly in the coefficient a_1 in the angular distributions for α_0 which requires natural parity. The elastic protons, inelastic protons, and neutrons would all be p waves—an assignment which is consistent with their respective partial widths. The estimated resonant proton-scattering cross section of about 50×10^{-27} cm/sr agrees satisfactorily with the observed anomalies. The assignment $T=1$ is indicated by the small upper limits that can be placed on the alpha-particle widths. With the assignment of 2^+ and $T=1$, the radiation γ_1 is an isotopic-spin-allowed $M1$ transition whose reduced width, $|M|^2 \approx 0.03$ Weisskopf units, is in the range of other such transitions.[18,19] The radiation γ_0 would be an $E2$ transition not enhanced by collective motion with a reduced width, $|M|^2 \approx 0.1$ Weisskopf units, that is also in the expected range. For no other assignment would the partial widths be as reasonable.

8. States at $E_x = 19.3$ MeV, $E_p = 3.6$ MeV

All the yield curves and energy dependences of the Legendre coefficients indicate a complex situation in this energy region. The large odd terms in the angular distributions for γ_1 and α_0 indicate that at least two levels of opposite parity are present. It is difficult to ascertain the resonance parameters for two broad, overlapping levels; hence, most of the values (Table III) given for these levels are only rough estimates. The radiation γ_0 is strong enough to require one of the levels to be 1^-, $T=1$. The interference terms in the angular distribution for α_0 require the other level to have even spin and positive parity. The large cross section for α_1 makes 0^+ unlikely because then $(2J+1)$ would be too small, and it also makes 4^+ unlikely since f-wave protons would give too small a proton width. Thus, 2^+ is the favored assignment and the large α width indicates $T=0$.

In closing this section it should be pointed out that it is by no means certain that all of the levels in this region have been identified. In particular, levels broader than about 1 MeV would be very difficult to detect. Such levels are indeed possible as the single-particle widths for both α_0 and α_1 are about 3 MeV and, in fact, the yield curve for α_1 indicates the presence of a continuum. It is mainly the $T=0$ levels that would be missed, and this may be the reason why the majority of levels that have been identified in this energy region have $T=1$.

A number of the assignments in this section have been based on plausibility arguments. In several cases the evidence is convincing; in the remaining cases the most probable assignments have been suggested.

IV. COMPARISON WITH THE PARTICLE-HOLE MODEL

Vinh-Mau and Brown[3] have calculated the spectrum of $T=1$ states in C^{12}. In extending these calculations, Gillet and Vinh-Mau[4] have concentrated on the odd-parity states of either isotopic spin, although they also included a few selected even-parity states. Goswami and Pal[5] give the 1^-, $T=1$, the 2^+, $T=0$, and the 3^-, $T=0$ states. For the same states, i.e., those having the same quantum numbers and similar configurations, the calculated energies are in reasonable agreement in the three investigations. (The levels of Goswami and Pal, however, are uniformaly higher because they fitted the first excited state of C^{12} exactly.) Classifying the states by quantum numbers, we compare the results of the particle-hole calculations with the results of the present experiment.

0^+ states. The only one-particle, one-hole configuration that can produce a 0^+ state is the $1s_{1/2}^{-1}2s_{1/2}$ configuration. Although the perturbed energy of this 0^+ state has not been computed,[3–5] the unperturbed energy of this configuration is 33.1 MeV, some 15 MeV above the observed 0^+ level. The perturbation cannot be expected to produce a shift of this amount. In fact, of the calculated states containing primarily a $1s_{1/2}$ hole, the lowest one is at about 23 MeV (the 0^- state mentioned below). Thus, the observed 0^+ state at 17.8 MeV is not predicted by the particle-hole model.

0^- states. The lowest 0^- state is predicted[4] at 23.3 MeV, about 5 MeV above the 0^- state observed at 18.3 MeV. It does not seem reasonable to identify these states with each other.

1^+ states. The well known 1^+, $T=1$ state at 15.1 MeV is calculated[3,4] to be at about 16.3 MeV; no other 1^+, $T=1$ states are expected[3] below about 29 MeV. This expectation is consistent with the failure to observe such levels in the region between 16.5 and 19.5 MeV. The theoretical predictions for the 1^+, $T=0$ levels are incomplete,[4] but the unperturbed energies indicate that none of these states are likely to appear in the region studied, in agreement with the failure to observe them.

1^- states. The theory[4] predicts no 1^-, $T=0$ states between 12.1 and 22.5 MeV, and none is found in the region studied. A 1^-, $T=1$ state whose major component is the $1p_{3/2}^{-1}2s_{1/2}$ configuration is predicted at 17.7 MeV (20.9 MeV in the work of Goswami and Pal). We observed two 1^-, $T=1$ states: one at 17.3 and one at 19.2 MeV. The next predicted 1^-, $T=1$ state, which is principally $1p_{3/2}^{-1}d_{5/2}$, is at about 22 MeV (25.1 MeV in the work of Goswami and Pal); this state is observed at 22.5 MeV and has been shown both experimentally[6] and theoretically[3–5] to be the major contributor to the giant dipole resonance. The gamma rays emitted from the states at 17.3 and 19.2 MeV exhibit approximately isotopic angular distributions, as would be expected for states formed chiefly from the $1p_{3/2}^{-1}2s_{1/2}$ configuration. Thus it appears that the predicted state may actually be a doublet. Similar and perhaps more complex splitting is observed[6] for the higher giant-resonance state, formed principally by the $1p_{3/2}^{-1}d_{5/2}$ configuration.

2^+ states. No 2^+, $T=1$ states are predicted between the well-known state at 16.1 MeV (calculated to be at about 16.4 MeV) and an excitation of 28 MeV. Thus, the observed state at 18.86 MeV is not predicted by the theory. Goswami and Pal predict 2^+, $T=0$ states at 18.9 and 24.1 MeV. One of these might correspond to the tentative 2^+, $T=0$ state at 19.5 MeV.

2^- states. The theory predicts 2^-, $T=1$ states at 18.2 and 19.3 MeV. Experimentally, a 2^-, $T=1$ state is found at 16.6 MeV. The large proton width of this state suggests that its major configuration is $1p_{3/2}^{-1}2s_{1/2}$, which is the major configuration of the state predicted at 18.2 MeV. The situation at about 19.5 MeV is complex and a 2^-, $T=1$ state could have been missed in the present work. In fact, the inelastic electron-scattering data is now[23] interpreted as indicating a 2^-, $T=1$ state in this region [see below]. No $T=0$ states are predicted; none are found.

3^- states. The theory predicts a 3^-, $T=0$ state at 19.5 MeV and a 3^-, $T=1$ state at 18.4 MeV. The 3^- state observed at 18.4 MeV with a probable assignment of $T=0$ is in satisfactory agreement with the theory. The state with natural parity at 18.7 MeV could well be 3^-, $T=1$.

V. DISCUSSION

In Fig. 11 the observed levels between the proton threshold and 19.5 MeV are compared with the particle-hole calculations.[3–5] For the sake of the discussion the levels observed at $E_x=15.1$, 22.5, and 25.5 MeV have also been included. The four lowest observed levels in Fig. 11 have all been previously assigned[1] and identified[3] with particle-hole levels. These four levels have also been identified with the first four states of B^{12}, and the assignments in C^{12} have been used to obtain assignments in B^{12}. Recently, the latter assignments have been substantially confirmed by Chase, True, and Warburton.[24] In both nuclei the two lowest levels, 1^+ and 2^+, have been identified with states formed principally from the $p_{3/2}^{-1}p_{1/2}$ configuration.[3,25] The next two levels, 2^- and

[23] J. D. Walecka and T. deForest, Jr. (private communication).
[24] L. F. Chase, Jr., W. W. True, and E. K. Warburton, Bull. Am. Phys. Soc. 9, 56 (1964).
[25] I. Talmi and I. Unna, Phys. Rev. Letters 4, 469 (1960).

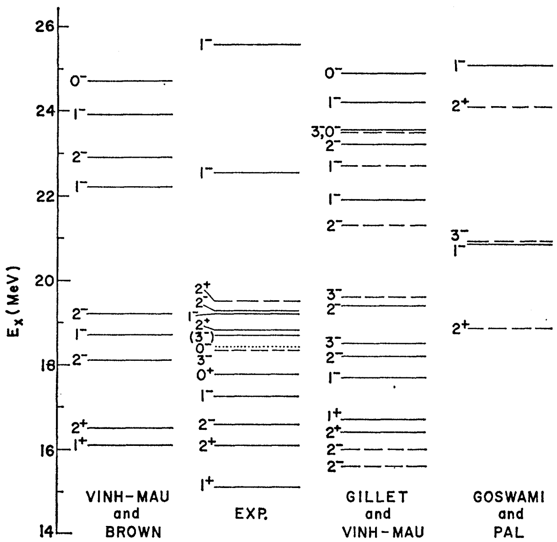

FIG. 11. Comparison of various calculated energy level schemes with the observed spectrum. The two lowest "exp" levels shown have previously been well established (Ref. 1), the two highest are from Ref. 6, the 2^- state at 19.2 MeV is from Ref. 23, and the remainder are from the present work. The dashed lines represent $T=0$ states, the solid lines $T=1$ states, and the dotted line a state whose isotopic spin has not been determined.

1^-, are attributed[3] to the $p_{3/2}^{-1}2s_{1/2}$ configuration in C^{12} and this assignment is supported by the experimental evidence which shows large proton widths and approximately isotropic angular distributions for these resonances. It is noteworthy that in B^{12} Talmi and Unna[25] made the same identification from independent considerations.

The gamma-ray strength of the 1^-, $T=1$ level at 19.2 MeV indicates that it makes an important contribution to the giant dipole resonance. The only way to account for this level within the framework of the particle-hole theory is to invoke a splitting of the $p_{3/2}^{-1}2s_{1/2}$ configuration. A level was seen in the same region in inelastic electron scattering by Goldemberg and Barber.[26] In this work an assingment of 1^-, $T=1$ was suggested. However, recently Walecka and deForest[23] have pointed out that the rapid increase in strength of this level with increasing momentum transfer in indicative of the 2^-, $T=1$ level predicted in this region. Thus, three levels have been identified in the 19.2–19.5-MeV region with the 2^-, $T=1$ level obscured in the $B^{11}+p$ work.

Also shown in Fig. 11 are the principal level of the giant dipole resonance observed at $E_x=22.5$ MeV and the somewhat weaker level at $E_x=25.5$ MeV. Both these resonances show[6] a gamma-ray angular distribution characteristic of the $p_{3/2}^{-1}d_{5/2}$ configuration and have accordingly been associated with the predominantly $p_{3/2}^{-1}d_{5/2}$ level predicted at $E_x=22.2$ MeV (Fig. 11). The calculated radiation width of the predominantly $p_{3/2}^{-1}d_{3/2}$ level predicted at $E_x=23.9$ MeV is very small and the level would not be expected to be seen in the gamma-ray experiments. However, Lewis and Walecka[27] have shown that the contribution from this level should increase markedly as the momentum transfer increases in the electron-scattering experiments, in agreement with the observations.[26,28] Thus, the level observed in electron scattering may not be the same as that observed in the (p,γ) experiments.

Assuming an oblate deformation for the C^{12} nucleus, Nilsson, Sawicki, and Glendenning[29] have computed the structure of the giant resonance. Although they do not find a clear-cut separation into two simple resonances for $K=0$ and $K=1$, the levels with $K=0$ are displaced upward from those with $K=1$. Below $E_x=29$ MeV the dipole strength is concentrated almost entirely in two strong $K=1$ levels at $E_x=22.2$ and 23.0 MeV and in in two weaker $K=0$ levels at $E_x=23.8$ and 26.3 MeV. Thus, the observed splitting of the main dipole resonance in C^{12} might arise from the deformity of the C^{12} nucleus. A similar separation of levels is predicted at lower energies, 17 MeV$<E_x<$20 MeV, but the predicted transition strengths are much smaller than those observed in this region.

Greiner[30] has discussed another source of doublet structure in the giant resonance. In O^{16} the calculations of Gillet and Vinh-Mau[4] show that the main 1^-, $T=1$ state of the giant resonance is nearly degenerate with a 1^-, $T=0$ state. If these states are pure, the latter state should have a very small radiation width. However, if there is significant mixing, the $T=0$ level can make a substantial contribution to the giant resonance, so that the two states would produce a doublet structure. Greiner has shown that agreement can be obtained with structure observed in O^{16}, and has suggested that a similar situation may exist in C^{12}. Indeed, just above the main 1^-, $T=1$ level in Fig. 11 there is a calculated 1^-, $T=0$ level which could be responsible for such structure. Clearly, more evidence is needed in order to understand the intermediate structure observed in the giant resonances in light nuclei.

Of the twelve levels observed in the region 12 MeV$<E_x<$1.95 MeV, only three levels (the two $J=0$ levels and the 2^+, $T=1$ level) appear to fall outside the scope of the particle-hole model. However, at this level of excitation in C^{12}, it is surely not surprising to find additional structure which could be due to more complex configurations. On the other hand, all the predicted particle-hole levels in the region 16 MeV$<E_x<$21 MeV have been at least tentatively accounted for.

Tyren and Maris[31] have indeed observed two reso-

[26] J. Goldemberg and W. C. Barber, Phys. Rev. **134**, B963 (1964).

[27] F. H. Lewis, Jr., and J. D. Walecka, Phys. Rev. **133**, B849 (1964).

[28] J. Goldemberg, Y. Torizuka, W. C. Barber, and J. D. Walecka, Nucl. Phys. **43**, 242 (1963).

[29] S. G. Nilsson, J. Sawicki, and N. K. Glendenning, Nucl. Phys. **33**, 239 (1962).

[30] W. Greiner, Nucl. Phys. **49**, 522 (1963).

[31] H. Tyren and Th. A. J. Maris, Nucl. Phys. **3**, 52 (1957); **4**, 637 (1957).

nances at $E_x = 19$ and 22 MeV in the inelastic scattering of protons from C^{12}, and the former resonance has been identified[3] with the missing 2^-, $T=1$ state and the latter with the main 1^-, $T=1$ state. In a detailed calculation, Sanderson[32] has shown that the observed angular distributions of the inelastic protons are consistent with attributing the lower resonance to the group of predicted levels in the range 18 MeV$<E_x<$20 MeV and the upper resonance to the group in the region 22 MeV$<E_x<$24 MeV. The main contributions to the two resonances arise from the 2, $T=1$ and 1^-, $T=1$ states, respectively. The recent work of Walecka and deForest[23] would confirm the presence of the 2^-, $T=1$ state.

[32] E. A. Sanderson, Nucl. Phys. **35**, 557 (1962).

ACKNOWLEDGMENTS

We would like to acknowledge conversations with Dr. W. C. Barber and Dr. J. D. Walecka on the recent status and interpretations of electron-scattering experiments on C^{12}. Thanks are also due to Dr. H. R. Blieden and Dr. H. W. Koch for sending us data prior to publication and to David Hanna for his assistance in analyzing the data.

PHYSICAL REVIEW VOLUME 139, NUMBER 4B 23 AUGUST 1965

(p,t) Ground-State $L=0$ Transitions in the Even Isotopes of Sn and Cd at 40 MeV, $N=62$ to 74*

G. Bassani,† Norton M. Hintz, C. D. Kavaloski,‡ J. R. Maxwell, and Glenn M. Reynolds
School of Physics, University of Minnesota, Minneapolis, Minnesota

(Received 29 March 1965)

The (p,t) reaction has been used to investigate the ground-state $L=0$ transitions in the seven even Sn isotopes and four even Cd isotopes with the University of Minnesota Linear Accelerator 40-MeV proton beam. Angular distributions have been taken in the range 7° to 25° in most cases, and the integrated cross sections used for comparison with the theory. The isotopes of Sn have a closed $Z=50$ proton shell and should be rather well described in terms of the neutrons outside of the $N=50$ shell. The detailed description of the neutron configurations is available from theoretical work and one-neutron transfer reactions. The agreement between pairing spectroscopic factors and the experimental cross sections is not good. It is clear that a distorted-wave Born-approximation analysis of the data is necessary, as well as, perhaps, a better understanding of the nuclear structure of the Sn isotopes. The Cd data show that an open proton shell decreases the number of $J=0$ coupled neutron pairs in the ground state.

I. INTRODUCTION

THE importance of the (p,t) reaction as a means of investigating certain properties of nuclear states has been demonstrated recently.[1] In particular the study of the (p,t) reaction can yield very useful information concerning the description of the neutron configuration in terms of correlated neutron pairs.

The even isotopes of tin are particularly interesting for a systematic study with the (p,t) reaction for several reasons. The 50 protons complete the filling of a major shell and should not be excited in the two-neutron pickup reaction. In addition, the low-lying states in these nuclei should be described quite well in terms of a mixed configuration of neutrons outside of the major closed shell of 50. A rather detailed description of the neutron configurations in these nuclei is available from theoretical calculations and one-neutron transfer reactions. This paper contains the results of an investigation of the (p,t) reaction on the seven even isotopes of tin and four even isotopes of cadmium using the 40-MeV proton beam of the University of Minnesota Linear Accelerator. Particular emphasis is placed on the ground-state transitions. The cadmium isotopes were studied in order to determine the effects of the nonclosed proton shell on the neutron configuration by comparison with the corresponding isotopes of tin.

In general the L value, that is the total orbital angular momentum for the transferred neutron pair, can be obtained from the shape of the angular distribution of the outgoing tritons. To the extent that the two neutrons in the triton are in a relative space-symmetric $S=0$ state, which is about 95% of the time,[2] $L=J$ (where $\mathbf{J}=\mathbf{L}+\mathbf{S}$) for the transferred neutron pair and the selection rule $|J_i-J_f|\leqq L\leqq(J_i+J_f)$ holds for the reaction. In the case of even-even targets these rules reduce to $L=J=J_f$. In addition, the selection rule $\Delta\pi=(-1)^L$ is valid in the approximation that the triton

* Supported in part by the U. S. Atomic Energy Commission.
† Present address: Centres d'Etudes Nucleaires, Saclay, France.
‡ Present address: Department of Physics, University of Washington, Seattle, Washington.
[1] G. Bassani, Norton M. Hintz, and C. D. Kavaloski, Phys. Rev. **136**, B1006 (1964).

[2] J. M. Blatt, G. H. Derrick, and J. N. Lyness, Phys. Rev. Letters **8**, 323 (1962).