as observed. In the same figure we have plotted also the nucleon polarization taking the neutron effective charges consistent with a hydrodynamic model of the recoil effect, i.e., $(-Z/A)$ for $E1$ and $(+Z/A^2)$ for $E2$. Use of a single effective neutron charge of 0.5 for both $E1$ and $E2$ essentially gives the same results as the one plotted in Fig. 3 as a solid curve.

Thus, within the context of the direct-reaction model and the limits of uncertainty of effective charges, the observed forward-peaking and the polarization data at 90° suggest that the photonuclear-reaction yield curve contains both $E1$ and $E2$ (and some $M1$) transition strength at γ-ray energies corresponding to and above the giant-dipole region.

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[1]C. P. Wu, F. W. K. Firk, and T. W. Phillips, Phys. Rev. Letters 20, 1182 (1968).

[2]R. C. Morrison, J. R. Stewart, and J. S. O' Connell, Phys. Rev. Letters 15, 509 (1965); R. C. Morrison, Ph. D. thesis, Yale University, 1965 (unpublished).

[3]M. G. Mustafa and F. B. Malik, Bull. Am. Phys. Soc. 14, 607 (1969).

[4]M. G. Mustafa and F. B. Malik, Phys. Rev. C 1, 753 (1970).

[5]J. E. E. Baglin and M. N. Thompson, Nucl. Phys. A138, 73 (1969).

[6]J. N. Jury, J. S. Hewitt, and K. G. McNeill, Can. J. Phys. 48, 1635 (1970).

[7]G. W. Cole, Jr., F. W. K. Firk, and T. W. Phillips, Phys. Letters 30B, 91 (1969).

[8]G. W. Cole, Jr., Ph. D. thesis, Yale University, 1970 (unpublished).

[9]G. W. Cole, Jr., and F. W. K. Firk, Bull. Am. Phys. Soc. 15, 481 (1970).

[10]M. G. Mustafa and F. B. Malik, Bull. Am. Phys. Soc. 15, 481 (1970).

[11]J. S. Levinger, *Nuclear Photodisintegration* (Oxford Univiersity Press, London, England, 1960).

[12]B. Buck and A. D. Hill. Nucl. Phys. A95, 271 (1967).

[13]A. R. Poletti, E. K. Warburton, and D. Kurath, Phys. Rev. 155, 1096 (1967).

[14]E. Hayward, in *Nuclear Structure and Electromagnetic Interactions*, edited by N. MacDonald (Plenum Press, Inc., New York, 1965).

[15]W. Stern, H. Miller, J. A. Rawling, and W. Buss, Bull. Am. Phys. Soc. 15, 769 (1970).

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Study of Particle-Emitting States in N^{12} and C^{12} Formed in Reactions of B^{10} with Helions

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The following reactions were studied. At $E_h = 6.2$ MeV: $B^{10}(h,n)N^{12}$. At $E_h = 10$ and 11 MeV: $B^{10}(h,n)N^{12}(p)C^{11}$, $B^{10}(h,p)C^{12}(n)C^{11}$, $B^{10}(h,p)C^{12}(p)B^{11}$, $B^{10}(h,p)C^{12}(\alpha)Be^{8}$, $B^{10}(h,p)C^{12}(d)B^{10}$. States at 5.3 MeV in N^{12} and 20.5 MeV in C^{12} were identified as members of an isobaric triad, with $J^{\pi}, T = 3^{+}, 1$ having a pronounced two-particle structure. Angular correlations support this assignment. For these and other states, branching ratios of the emitted particles are measured, and conclusions on isospin purities and other properties are drawn.

I. INTRODUCTION

Nuclear transfer reactions are often used to yield information on quantum numbers and wave functions of the states populated in the final nucleus. If a final state is unstable to particle emission, additional or supplementary information can be gained by measuring correlations between the first and second emitted particles. This will be of particular importance if the state cannot be formed by elastic scattering on a neighboring nucleus. This is true for the nucleus N^{12}, most of the states being unstable toward proton emission into the β-unstable nucleus C^{11}. Population of these states by the reaction $B^{10}(h,n)$ will be suitable for revealing two-particle correlations in these states, while their decay may exhibit their structural relationships to the states of C^{11}.

In the same experiment in which we therefore studied the reaction $B^{10}(h,n)N^{12}(p)C^{11}$, we also observed the mirror reaction $B^{10}(h,p)C^{12}(n)C^{11}$, populating presumably analog states and leading to the same final states. In this case proton decay to the respective states in B^{11} is also possible, as well as α decay to Be^8, and in a few cases deuteron decay back to B^{10}. From observation of all these features general information on highly excited particle unstable states could be expected. The (h,n) and (h,p) reactions on B^{10} fortunately can be compared with a recent study[1] of the reaction $B^{10}(t,p)B^{12}$ leading to states presumably analogous to those of N^{12} and C^{12}.

II. EXPERIMENTS

The present study involved: (i) neutron time-of-flight measurements of the reaction $B^{10}(h,n)N^{12}$ at $E_h = 6.2$ MeV, (ii) coincidence measurements between neutrons and charged particles x in reactions of the type $B^{10}(h,nx)$, and (iii) coincidence measurements between two charged particles x, y in a process of the type $B^{10}(h,xy)$, both at $E_h = 10$ and 11 MeV. The accelerator used is a 5.5-MV van de Graaff generator. It can be used in conjunction with terminal pulsing and a Mobley bunching system to produce nanosecond pulses of singly charged helions.[2] It also can be operated, by means of a terminal analysis magnet, to produce dc beams of doubly charged helions. The target consisted of B^{10} enriched to 94%. It was evaporated as a layer of unknown thickness on a Ta backing for the experiment of type (i) and as a self-supporting foil of (30 ± 5)-$\mu g\,cm^{-2}$ thickness for type (ii) and (iii).

In measurement (i) the neutrons were detected by liquid scintillators (Ne 213, 1 in. × 4 in. diam) after a flight path of 6 m; the threshold for the recoil protons was set at 700 keV. Pulse-shape discrimination was used to discriminate against γ-radiation background. In measurement (ii) the h beam was focused onto a target in the center of a cylindrical vacuum chamber. Neutrons were again detected by NE-213 scintillators (2 in. × 5 in. diam) placed outside the chamber in its median plane 60 cm from the center. Charged particles were detected and identified by two solid-state detector telescopes (ΔE counter 20 μ, E counter 1000 μ) placed inside the chamber, that could be moved independently in the median plane around the target.[2a]

The summed energy signals from the telescope were fed into one input of a two-dimensional multichannel analyzer. The time difference between a fast signal from the E detector and a corresponding signal from an associated neutron in the scintillator was measured with a conventional time-to-pulse-height converter and fed into the other input of the analyzer. Coincident events were stored in a two-dimensional array containing 32 channels for the time-of-flight difference and 128 channels for the charged-particle energy. A multiplication signal from a particle identifier circuit ensured that only proton signals were stored in this part of the experiment. The thresholds were 1.5 MeV in the telescope and 600 keV in the scintillator circuit; the over-all time resolution was ≤ 3 nsec.

In measurement (iii), correlated events detected in the two telescopes were registered, using a coincidence time covering the flight time of the fastest (10-MeV protons) and the slowest (3-MeV α) particles to be investigated. Here the digitized energy signals were fed into a PDP-9 computer and registered in an array of 512×512 channels, with additional bits characterizing the identification as protons, deuterons, helions, or α particles. From a storage buffer the events were stored on magnetic tape and evaluated off-line.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. Results from $B^{10}(h,n)N^{12}$ and Comparison with $B^{10}(h,p)C^{12}$ and $B^{10}(t,p)B^{12}$

Figure 1 gives as an example the neutron time-of-flight spectrum observed at 0°. All known states in N^{12} as given in the recent compilation of Ajzenberg and Lauritsen[3] have been identified. In addition we found levels at 4.3 and 5.3 MeV which have also been observed in a most recent measurement of the $C^{12}(h,t)N^{12}$ reaction by Ball and Cerny.[4] Further states observed in the coincidence experiment are quoted in Sec. 3 B4.

Predominantly populated is the state at 5.3 MeV which has been excited very weakly in the (h,t) reaction. Angular distributions were evaluated only for this state and for the ground state, shown in Figs. 2 and 3. The solid lines represent distorted-wave Born-approximation (DWBA) calculations using the code DWUCK[5] with optical-model parameters listed in Table I. The framework of the theory of Glendenning[6] was used which gives the cross section in the form

$$\frac{d\sigma}{d\Omega} \propto \sum_{LSJT} C_{ST}{}^2 \sum_{\mu} \left| \sum_{N} G_{NLSJT} B_{NL}^{\mu} \right|^2$$

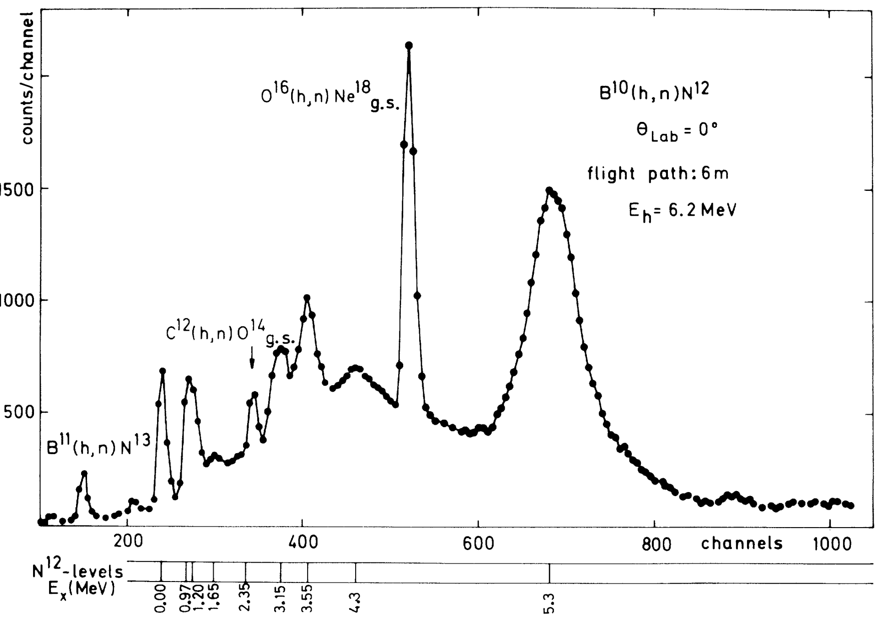

FIG. 1. Neutron time-of-flight spectrum. Levels in N^{12} and background lines are indicated.

(notation of Ref. 6). In the DWBA amplitude B_{NL}^{μ}, the form factor for the two nucleons transferred was calculated by a code of Sichelschmidt.[7] In this code the usual oscillator wave functions are replaced by eigenfunctions of a Woods-Saxon well that are developed into an oscillator basis. It turned out that the best fit was obtained by assuming that in the formation of the strong state at 5.3 MeV the two protons were transferred in the configuration $(1p_{1/2})^2{}_{JTL=010}$, and in the formation of the ground state they were transferred in the simple shell-model configuration $(1p_{3/2}1p_{1/2})_{JTL=212}$.[8] For the excited state at 5.3 MeV, therefore, quantum numbers J^{π}, $T=3^+, 1$ can be deduced, taking into account the $3^+, 0$ ground state of the target nucleus B^{10} and the strong selection rules of the (h,n) reaction.[6] Strong two-particle structure for the 5.3-MeV state would imply rather weak excitation in the $C^{12}(h,t)N^{12}$ reaction, as is born out by experiment.[4]

It is noteworthy that Middleton and Pullen,[1] in the mirror reaction $B^{10}(t,p)B^{12}$ at $E_t=10$ MeV, have observed predominant formation of a state in B^{12} at 5.61 MeV with apparently the same properties. Therefore we conjecture these states to be members of an isobaric triad having $T=1$, T_z

TABLE I. Optical potential parameters for two-nucleon transfer reactions on B^{10}. (See Ref. a.)

	E (MeV)	V_0 (MeV)	r_0 (fm)	a_0 (fm)	W' (MeV)	r' (fm)	a' (fm)	V_{so} (MeV)	r_C (fm)
$t+B^{10}$ [b]	10	150	1.22	0.73	20	1.25	0.81	24	1.3
$\tau+B^{10}$ [b]	14	150	1.22	0.73	20	1.25	0.81	24	1.3
$\tau+B^{10}$ [b]	11	150	1.22	0.73	20	1.25	0.81	24	1.3
$\tau+B^{10}$ [b]	6.2	120	1.22	0.73	20	1.25	0.81	24	1.3
$p+B^{12}$ [c]	10	46	1.29	0.66	36	1.25	0.5	24	1.3
$p+C^{12}$ [c]	9	46	1.29	0.66	36	1.25	0.5	24	1.3
$n+N^{12}$ [c]	6	46.5	1.29	0.66	36.5	1.25	0.5	24	1.3
$n+N^{12}$ [c]	1	47	1.29	0.66	37	1.25	0.5	24	1.3
$(2p)$ (pn) $(2n)$	bound		1.25	0.65			$\lambda_{so}=25$		

[a]See R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. Nr3240, 1962 (unpublished).

[b]Values chosen with reference to the tables of P. E. Hodgson, Advan. Phys. 17, 563 (1968).

[c]Values calculated with formulas of D. Wilmore and P. E. Hodgson, Nucl. Phys. 55, 673 (1965); Ann. Rev. Nucl. Sci. 17, 10 (1967).

$=\pm 1$. The corresponding state with $T_z = 0$ is expected in C^{12} at an excitation energy around 20 MeV. This may be identified with a state found at 20.6 MeV by Comfort and Baglin[9] to be populated strongly in $B^{10}(h,p)C^{12}$ at $E_h = 13.9$ MeV. [In the present work we do see such a state, which we would like to assign an excitation energy of 20.5 ± 0.1 MeV. In the singles spectra it is covered at many angles by lines from $C^{12}(h,p)$ and $O^{16}(h,p)$ due to target contaminants. In the coincidence spectra discussed below, it shows up very clearly, however.] From these qualitative arguments it may be concluded that we have the complete $J^\pi, T = 3^+, 1$ triad before us.

Further evidence may be taken from a DWBA analysis of the differential cross sections of Refs. 1 and 9, which we have performed with the parameters listed in Table I and using the same wave functions in all cases. The results are shown in Figs. 4 and 5. The nice agreement is further support of the assumed equal structure for these states.

All relevant properties of these states being equal, the cross sections for two nucleon transfer reactions should be determined solely by the spin-isospin factor[6,10]

$$C_{ST}^2 = b_{ST}^2 \left| \begin{pmatrix} T_i & T & T_f \\ T_{zi} & T_z & T_{zf} \end{pmatrix} \right|^2 .$$

The isospin Clebsch-Gordan coefficients being identical (=1) in this case, C_{ST}^2 turns out to be 1 for (h,n) and (t,p), and $\frac{1}{2}$ for (h,p). Hence it is expected that the cross sections for (h,n) and (t,p) should be equal and twice the value for (h,p). The results of Refs. 1 and 9 imply a ratio $\sigma(t,p)/\sigma(h,p) \approx 3.5$. A rough estimate of the (h,n) and (h,p) cross section at 11 MeV based on the coincidence measurements described below gives a ratio $\sigma(h,n)/\sigma(h,p) \simeq 3$, which is in surprisingly good

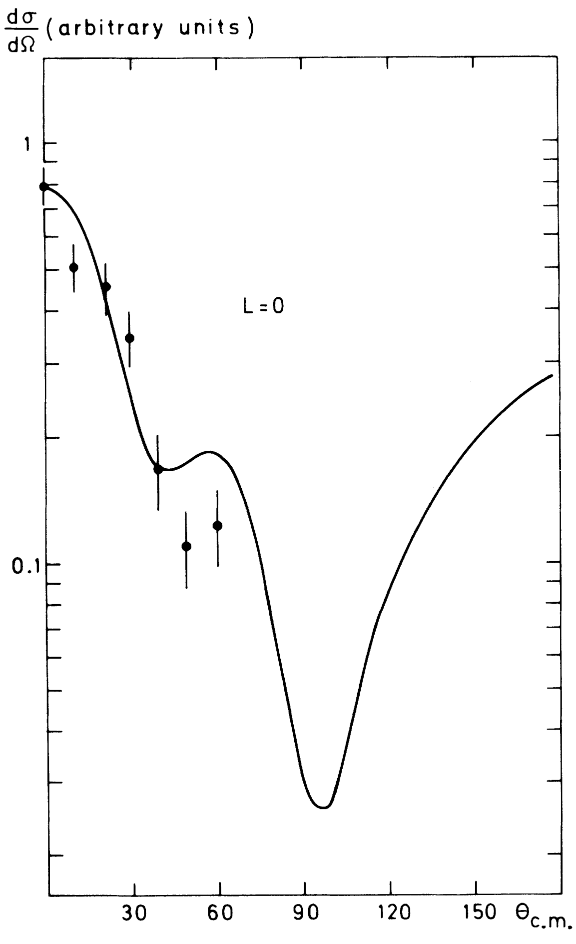

FIG. 2. Angular distribution of neutrons from $B^{10}(h,n)N^{12}$, final state at 5.3 MeV. Solid line represents DWBA calculation.

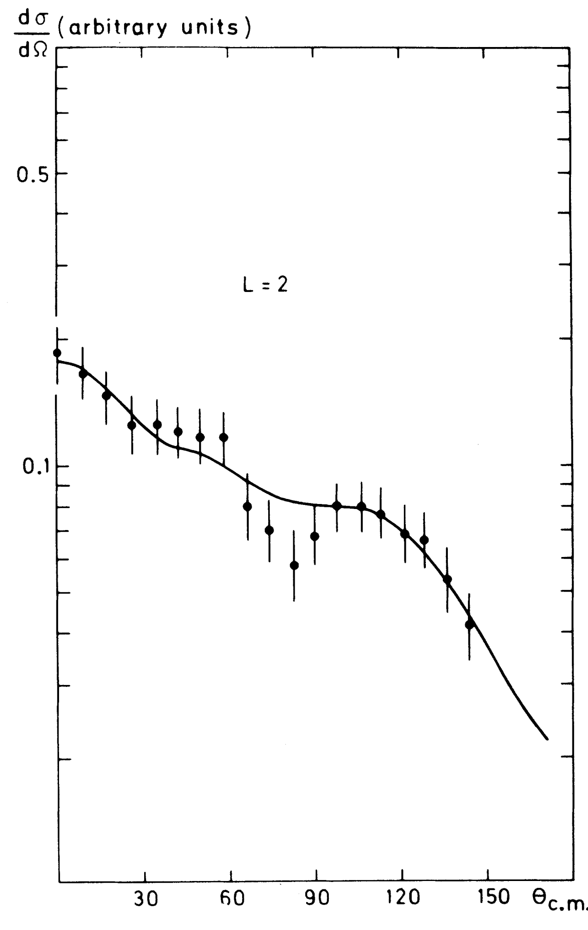

FIG. 3. Angular distribution of neutrons from $B^{10}(h,n)N^{12}$, ground state. Solid line represents DWBA calculation.

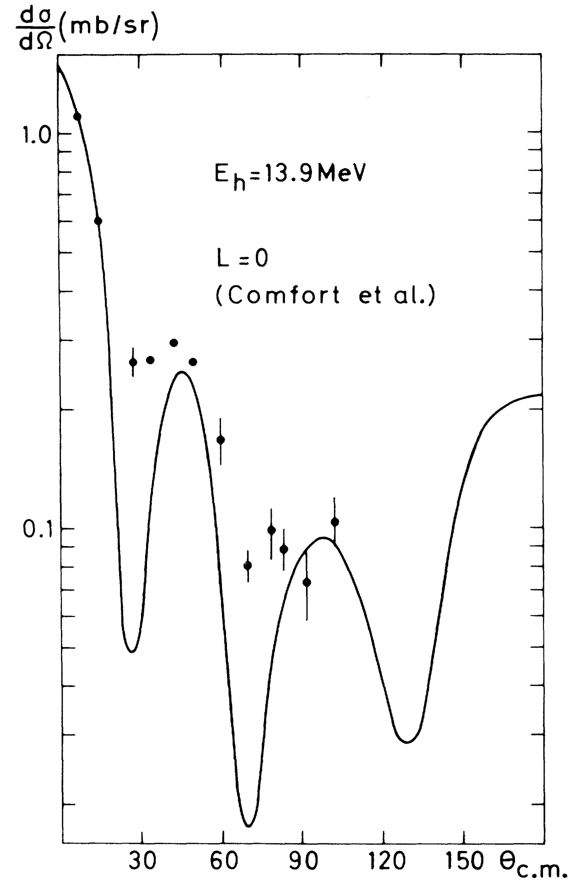

FIG. 4. Angular distribution of protons from $B^{10}(h,p)C^{12}$, final state at 20.6 MeV (supposed analog to the 5.3-MeV state in N^{12}). Data from Ref. 9. Solid line represents DWBA calculation.

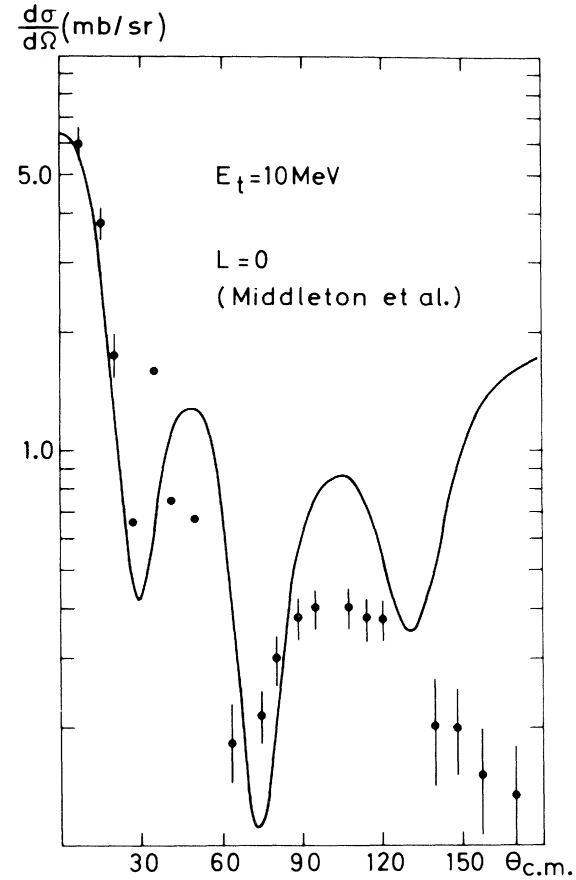

FIG. 5. Angular distribution of protons from $B^{10}(t,p)B^{12}$, final state at 5.61 MeV (supposed analog to the 5.3-MeV state in N^{12}). Data from Ref. 1. Solid line represents DWBA calculation.

agreement with this ratio. Thus the Glendenning theory[6] appears to be an appropriate description for these transitions.

In a recent paper Cohen and Kurath[11] predict a rather large spectroscopic amplitude for two-nucleon transfer to a state with $J^\pi, T = 3^+, 1$ located theoretically at 19.63 MeV in C^{12}. It may be concluded that we have here this state and its analogs, because such energy deviations are to be expected, taking into account that the theoretical values are derived from an intermediate-coupling calculation for the whole p shell.

B. Results of the Two-Dimensional Measurements

1. *Survey and Typical Examples*

Two-dimensional spectra were stored separately for the following outgoing reaction channels, resulting from $B^{10}+h$:

(*a*) $p+n+C^{11}$ $\quad Q_{g.s.} = 0.975$ MeV,

(*b*) $p+p+B^{11}$ $\quad = 3.738$ MeV,

(*c*) $p+d+B^{10}$ $\quad = -5.494$ MeV,

(*d*) $p+\tau+Be^{9}$ $\quad = -6.587$ MeV,

(*e*) $p+\alpha+Be^{8}$ $\quad = 12.326$ MeV,

(*f*) $d+\tau+Be^{8}$ $\quad = -6.028$ MeV,

(*g*) $d+\alpha+Be^{7}$ $\quad = -4.346$ MeV.

Only for the channels *a*, *b*, *c*, and *e* was the cross section large enough to show up above the background of accidental coincidences.

Figure 6 shows, as an example, a two-dimensional display of proton energy and neutron time of flight corresponding to channel (*a*). The coincident events are seen to be located on four kinematic loci, related to five states in the final nucleus C^{11}. It is seen that the intensity varies strongly

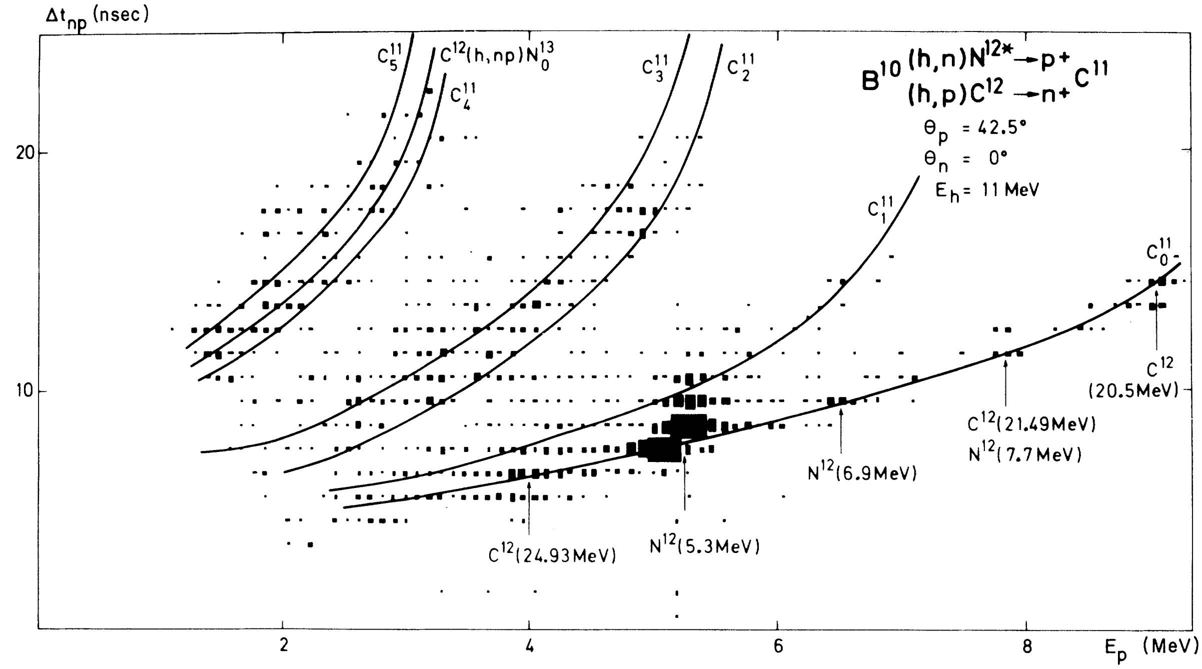

FIG. 6. Two-dimensional display of proton energy and neutron time of flight in the reactions $B^{10}+h \to C^{11}+n+p$. Solid lines marked C_i^{11} represent transitions to the ith excited state in C^{11}. Intermediate states in C^{12} and N^{12} are indicated by arrows.

along these loci, indicating sequential reactions to be predominant.[12] They involve either states in C^{12} [channel a_1:$B^{10}(h,p)C^{12}(n)C^{11}$], or in N^{12} [channel a_2: $B^{10}(h,n)N^{12}(p)C^{11}$].

Figure 7 shows the projected spectrum of one of these plots onto the proton energy axis. Strongest were, as mentioned above, transitions through the states at 20.5 MeV in C^{12} and at 5.3 MeV in N^{12}. The weak lines could be assigned to several states in C^{12} and N^{12} by the kinematic behavior at different angles.

In channel (b) also, the same state at 20.5 MeV was strongest in the reaction $B^{10}(h,p)C^{12}(p)B^{11}$. Because of the identity of the two protons each line appeared twice on the kinematic locus, making the analysis more difficult in this case.

Channel (c) was quite strong, but could not be resolved from the reaction $C^{12}(h,p)N^{14}(d)C^{12}$, so that no quantitative information could be extracted. The relatively strong occurrence of these deuteron channels could be easily explained with the assumed mechanism for the (h,p) reaction, where an (np) cluster is transferred, forms an intermediate state, and is subsequently emitted again.

Channel (e) results in a four-particle state, as the Be^8 nucleus is unstable against α decay. Events from a nonsequential reaction mode therefore could have been scattered over the whole array. However, the very weak reaction appeared to be confined predominantly to the kinematic locus corresponding to the process $B^{10}(h,p)C^{12}(\alpha)Be^8$g.s. The same preference for the sequential mode in this channel has been observed by Waggoner *et al.*,[13] who investigated this reaction thoroughly populating lower excited states in C^{12}. Predominant sequential α decay of C^{12} states through Be^8 was also observed by Epstein *et al.*[14] in the reaction $B^{11}+p \to C^{12} \to Be^8+\alpha$.

2. *Angular Correlations*

Only for the two strongest lines in channels (a_1) and (a_2) could complete angular correlations be evaluated; they are given in Fig. 8. For the 20.5-MeV state in C^{12} (channel a_1) the angular correlation is isotropic. This is expected for $L=0$ transfer in the (h,p) reaction, and thus corroborates the assignment $J^\pi=3^+$ discussed earlier.

The angular correlation related to the proposed analog state at 5.3 MeV in N^{12}, however, is neither isotropic nor even symmetric about 90°. This fact immediately implies the presence of two overlapping states of opposite parity. Such a phenomenon has been discussed by Huby and Liu[15] with respect to a similar case which we had observed in the reaction $C^{12}(d,n)N^{13}(p)C^{12}$, where two overlapping states with $\frac{3}{2}^-$ and $\frac{5}{2}^+$ were involved.[16] Huby and Liu[15] have shown that a very weak excitation of the level of opposite parity is able to cause

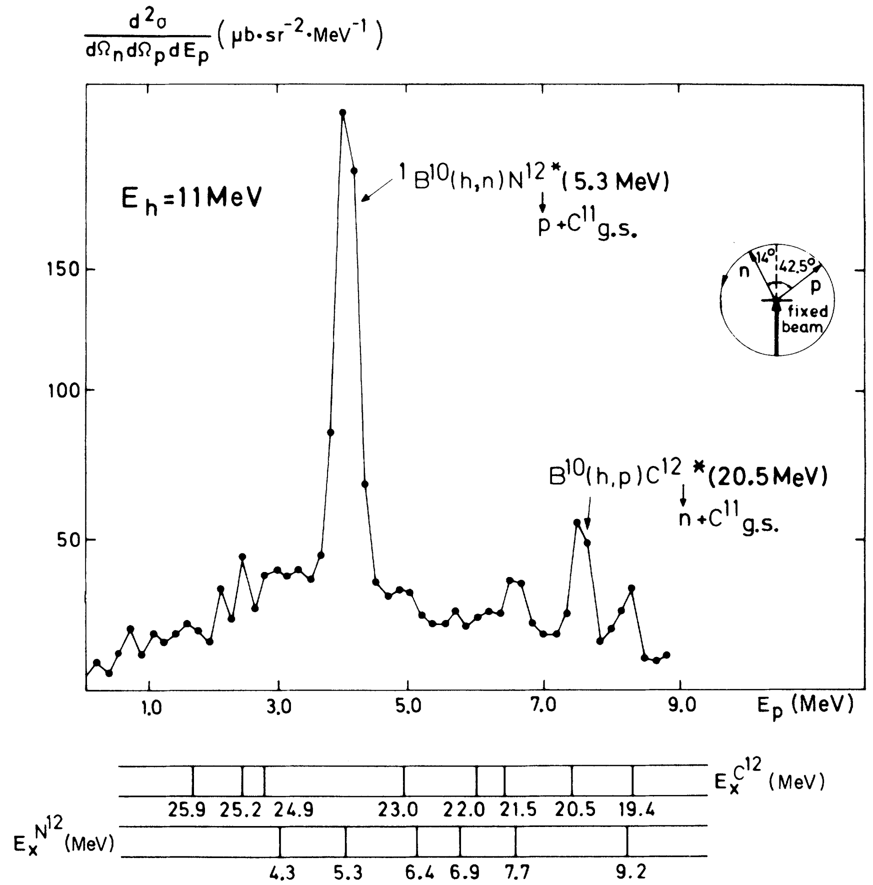

FIG. 7. Energy distribution of coincident particles emitted in the reaction $B^{10}(h,np)C^{11}$ (ground state). The distribution along the kinematic locus related to the ground state of C^{11} was projected onto the proton energy axis, with background due to random coincidences subtracted. Intermediate states in C^{12} and N^{12} are indicated.

large asymmetries. The occurence of such a state is not unlikely, taking into account the large width of the state discussed so far (≈250 keV)[17] and therefore does not alter the earlier considerations on this state.

While in the N^{13} case the situation could be checked by direct scattering of protons on C^{12}, this is not possible here, as N^{12} has no suitable stable neighbors. Note that the asymmetry, and thus the mixture, does not change appreciably at $E_h = 10$ MeV.

Fitting the angular correlation by Legendre polynomials in principle should give information on the angular momenta involved and on the mixing ratio. However, because of the large spin (3^+) of the target nucleus, there is so large a variability in the angular momentum values that no definite conclusions can be drawn, as was pointed out by Liu.[18]

From the measured angular correlation one may get a rough estimate for the cross section of the (h,n) and (h,p) reactions at 11 MeV. Assuming azimuthal isotropy one obtains, by integration over neutron angles, $d\sigma(h,p)/d\Omega = 0.2$ mb/sr at $\theta_p = 42.5°$. By means of a DWBA calculation to extrapolate to 0°, a value of 1 mb/sr at 0° is obtained, only slightly smaller than Comfort and Baglin's[9] value at 14 MeV. In a similar way, but with larger uncertainty due to the anisotropic correlation, one can estimate the cross section at 11 MeV for the (h,n) reaction to be 3 mb/sr. The ratio thus agrees with the corresponding ratio of the (t,p) and (h,p) reactions mentioned above.

3. Branching Ratios

The other states in N^{12} and C^{12} seen in Fig. 7 and corresponding spectra at other angles were too

TABLE II. Relative intensities in the decay of some C^{12} states to ground states of the final nuclei. $B^{10}(\tau,p)$-C^{12*}; $C^{12*}(p_0)B^{11}$, $C^{12*}(n_0)C^{11}$, $C^{12*}(\alpha_0)Be^8$. One proton detector at 42.5° lab; the other detector at 42.5° (proton and α) or 44° (neutron) on the opposite side of the beam. The energy identification in the case of pp coincidences being twofold ambiguous, the respective states are grouped together. Statistical error estimated 20%.

E_x (MeV) in C^{12*}	$C^{12*}(p_0)B^{11}$ $\theta_p=42.5°$ $\theta_p=-42.5°$	$C^{12*}(n_0)C^{11}$ $\theta_p=42.5°$ $\theta_n=-44.0°$	$C^{12*}(\alpha_0)Be^8$ $\theta_p=42.5°$ $\theta_\alpha=-42.5°$
20.5/23.5	0.95	1.0	
21.5/22.6	0.9	0.22	≤ 0.02
23.0/20.99	0.62	0.25	
23.9/20.24	0.38	0.3	

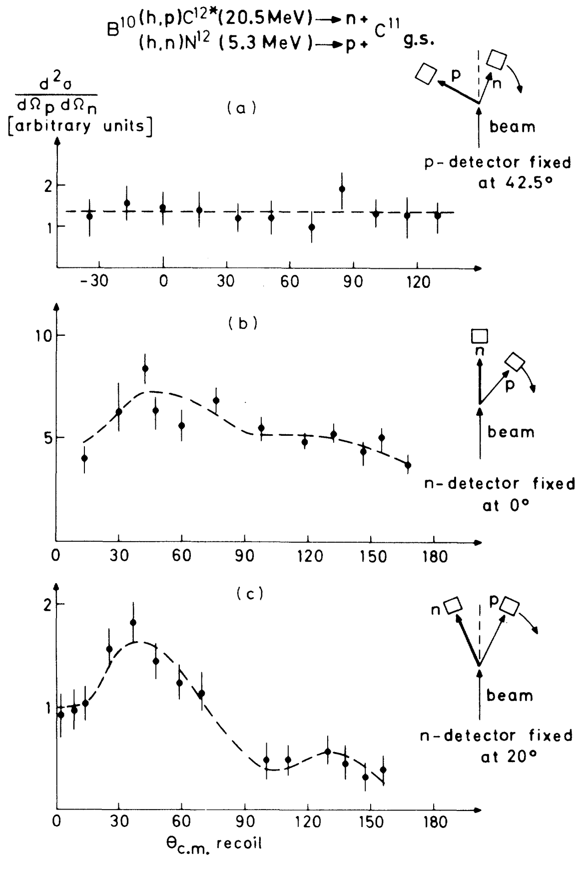

FIG. 8. Angular correlations in the sequential reactions $B^{10}(h,np)C^{11}$. Detector position as indicated in the inserts. (a) $B^{10}(h,p)C^{12*}_{20.5\ MeV}(n_0)C^{11}_{g.s.}$, proton detector fixed at 42.5° lab, neutron moving, (b) $B^{10}(h,n)^{12*}_{5.3\ MeV}(p_0)$-$C^{11}_{g.s.}$, neutron detector fixed at 0° lab, proton moving, (c) same as (b), neutron detector fixed at 20°. The angular scale refers to the c.m. system of the respective recoil nucleus, C^{12*} or N^{12*}; cross sections were transformed to these systems.

weakly excited for a complete angular-correlation measurement. In Table II we therefore only list representative intensities observed at roughly equivalent angles for C^{12} states decaying by proton, neutron, and α emission to the ground state of the respective final nuclei. Assuming the angular correlations not to be too anisotropic these data should be roughly proportional to the total cross section.

Comparison with the numerous states in the giant resonance region quoted by Ajzenberg-Selove and Lauritsen[3] shows that rather few states are excited in the (h,px) reaction at all. In all cases the α decay is very weak, which supports the assignment of predominantly $T=1$ to these states. ($T=0$ states in this excitation region should be much broader, because of the unhindered α decay.) For pure $T=1$ states, however, the neutron and proton decay should be the same, apart from barrier penetration effects that should amount to 30% in this region.[19] This requirement is well fulfilled for the 20.5-MeV state, corroborating the pure $T=1$ character deduced from the two-nucleon transfer investigation into this state and its analogs.

For other states under discussion a marked difference in neutron and proton decays is apparent. This can be made plausible qualitatively by assuming a small amount of $T=0$ admixture. Barker and Mann[19] have shown that the different cross-section ratio for the reactions $C^{12}(\gamma,n)$ and (γ,p) involving dipole states in this energy region can be explained by such an isospin impurity.

Another interesting feature is the branching ratio of both neutron and proton decays to the various excited states of C^{11} and B^{11}, respectively. Only for states above 22-MeV excitation energy in C^{12} was an observation of the decay to excited states possible. Owing to the very small intensities we only list in Table III the relative values for C^{12} states between 22 and 25 MeV as observed at various angles grouped together.[20] It is seen that in both channels the first excited state in the $A=11$ nuclei is populated weakly. This appears to be

TABLE III. Branching ratio of the decay of C^{12*} states into excited states of the respective final nucleus C^{11} or B^{11}. The n and p channels are not normalized to each other in this case. Intensities are averaged over the excitation energy between 22 and 25 MeV in C^{12}. Statistical error estimated 15%.

J^π, C^{11}, and B^{11}	E_x (MeV) in C^{11}	$C^{12*}(n_i)C^{11}$ relative intensity	E_x (MeV) in B^{11}	$C^{12*}(p_i)B^{11}$ relative intensity
$\frac{3}{2}^-$	0.0	1.0	0.0	1.0
$\frac{1}{2}^-$	1.995	0.1	2.124	0.1
$\frac{5}{2}^-$	4.305	0.7	4.444	0.8
$\frac{3}{2}^-$	4.794		5.019	

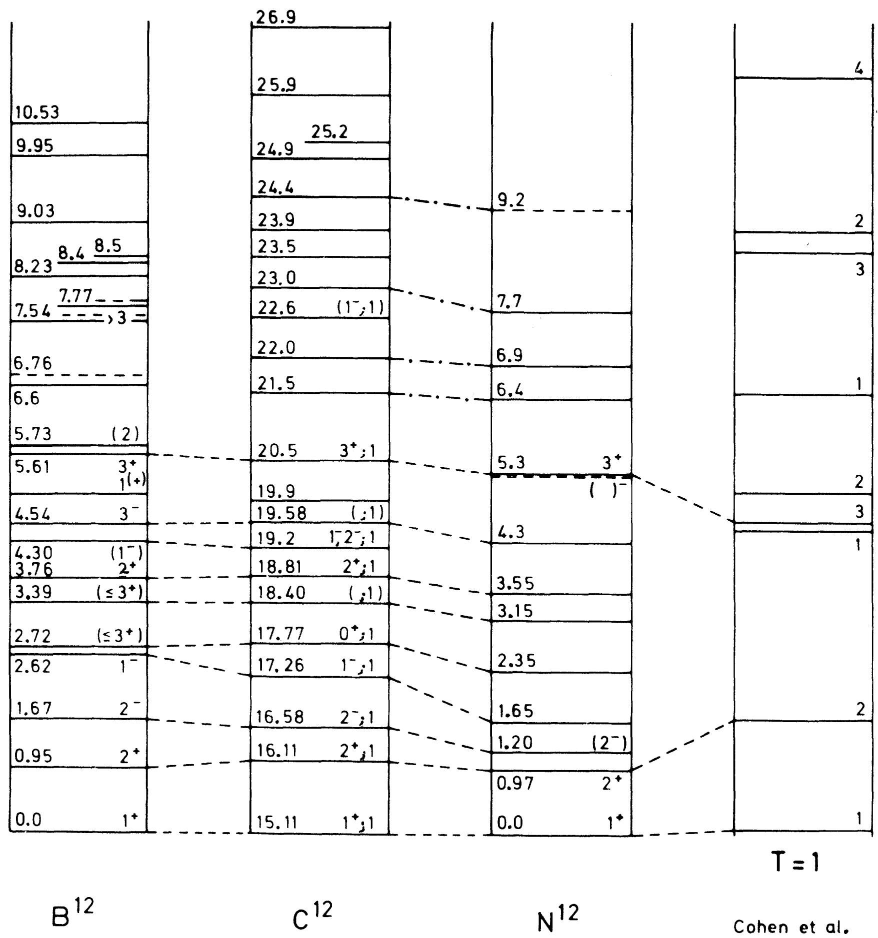

FIG. 9. Energy levels of the $A=12$ nuclei, from Ref. 18. Levels in N^{12} found in this work: see text. The level indicated by a dashed line close to 5.3 MeV and its parity was derived from an analysis of the angular correlation. The $T=1$ levels on the right are theoretical predictions from Ref. 11. Analog states are connected by dashed lines; tentative connections are indicated by dot-dashed lines.

hard to explain by angular momentum selection rules alone, and might indicate a significant structural difference.

4. *Level Scheme of* N^{12}

Sequential decays through hitherto unknown states in N^{12} at 6.4, 6.9, 7.7, and 9.2 MeV (uncertainty of about ±50 keV) were identified (see Fig. 7, bottom scale). From the way their position varied with emission angle this decay mode could be established. In Fig. 9 we display the complete level scheme of N^{12} together with the corresponding scheme of C^{12} and B^{12}. The well established analog states[4] have been connected by dashed lines. The dot-dashed lines have been tentatively drawn connecting supposed analog states.

IV. CONCLUSION

The prominent feature of this work is the existence of an isobaric triad with J^{π}, $T=3^{+}, 1$ in the $A=12$ nuclei, which has a very pronounced two-particle structure. This assignment is based on the analysis of two-nucleon transfer reactions and on the decay properties of these states. It is consistent with predictions of Cohen and Kurath[11] derived from intermediate-coupling calculations for the p shell.

That the other states discussed are populated so weakly in $B^{10}(h,p)C^{12}$ suggests that they do not have a notable two-particle structure. The experimental result that the giant dipole resonance does not show up markedly implies that its pure one-particle–one-hole states[21] are not excited in the two-nucleon transfer reaction, as has been pointed out already by Comfort and Baglin.[9] Thus the nature of the states seen in this work probably is a mixture of different components of various structures, as is suggested by the proposed isospin impurity.

For a more thorough understanding on the experimental side investigations at higher h energy would be worthwhile, and on the theoretical side predictions on the branching ratios based, e.g., on the Cohen-Kurath[11] or Gillet[21] wave functions will be needed.

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[1]R. Middleton and D. Pullen, Nucl. Phys. 51, 50 (1964).

[2]H. Fuchs, K. Grabisch, P. Kraaz, and G. Röschert, Nucl. Phys. A105, 590 (1967).

[2a]W. Bohne *et al.*, Nucl. Phys. A113, 97 (1968).

[3]F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. A114, 1 (1968).

[4]G. C. Ball and J. Cerny, Phys. Rev. 177, 1466 (1969).

[5]DWUCK: Distorted Waves University of Colorado's Spin-Orbit Version, author, P. D. Kunz (1967); modified by W. and T. Nuclear Research Centre; University of Alberta (1967); modified by G. Röschert, Hahn-Meitner-Institut für Kernforschung, Berlin, Germany (1969/70).

[6]N. K. Glendenning, Phys. Rev. 137, B102 (1965).

[7]F. Sichelschmidt, Ph.D. thesis, Hahn-Meitner-Institut für Kernforschung, 1970 (unpublished).

[8]Mixing in of configurations $(d_{5/2})^2$ and $(2s_{1/2})^2$ did not yield significant change in the shape of the distribution; however, changes of an order of magnitude in the cross section value were observed. The absolute normalization of the DWBA calculation is not very reliable, so that nothing can be said about such admixtures.

[9]J. R. Comfort and J. E. E. Baglin, Bull. Am. Phys. Soc. 12, 34 (1967); and private communication.

[10]D. G. Fleming, J. Cerny, and N. K. Glendenning, Phys. Rev. 165, 1153 (1968); and D. G. Fleming, dissertation, University of California, Berkeley, 1967 (unpublished).

[11]S. Cohen and D. Kurath, Nucl. Phys. A141, 145 (1970).

[12]Nonsequential modes related to formation of the singlet deuteron ($B^{10}(h, d)C^{11}$) were observed only at very small relative angles between neutron and proton. This is discussed in an earlier paper. See W. Bohne *et al.*, Phys. Rev. Letters 24, 1028 (1970).

[13]M. A. Waggoner, J. E. Etter, H. D. Holmgren, and C. Moazed, Nucl. Phys. 88, 81 (1966).

[14]M. Epstein, H. D. Holmgren, M. Jain, H. G. Pugh, P. G. Roos, N. S. Wall, C. D. Goodman, and C. A. Ludemann, Phys. Rev. 178, 1698 (1969).

[15]R. Huby and Q. K. K. Liu, Nucl. Phys. A122, 145 (1968).

[16]W. Bohne *et al.*, Nucl. Phys. A106, 442 (1967).

[17]In C^{12} and B^{12} the analogs of the odd-parity state need not necessarily overlap with the 3^+ state, but may well be found among the numerous weakly populated states in the neighborhood.

[18]Q. Liu, private communication.

[19]F. C. Barker and A. K. Mann, Phil. Mag. 2, 5 (1957).

[20]The neutron decay of C^{12} levels to excited states in C^{11} is mixed up with the proton decay of N^{12} levels, an experimental separation of these two channels being impossible.

[21]V. Gillet and N. Vinh-Mau, Nucl. Phys. 54, 321 (1964).