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Study of the $^{12}C(h,p)^{14}N$ Reaction Mechanism by a Systematic Use of the $p-\gamma$ Angular-Correlation Method

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The mechanism of the reaction $^{12}C(h,p)^{14}N$ has been studied by measuring the alignment of the 10 bound states of ^{14}N, at 32 incident energies in the range $3 \le E_h \le 11$ MeV. These alignments were measured by the angular-correlation technique, using a collinear geometry with detection of the outgoing protons at 0° as well as at 180°. The theoretical alignments which have been calculated both by the direct-interaction model and by the compound-nucleus statistical model, and which are quite different in these two models for levels of natural parity, are almost constant with energy. However, experimentally, strong fluctuations of the alignment have been observed. For the incident energies used in this work, where the mechanism is usually considered intermediate between these two extreme models, it seems that the reaction $^{12}C(h,p)^{14}N$ proceeds predominantly by the compound nucleus ^{15}O. The giant-resonance structure, or the predominant $[p \otimes {}^{14}N]$ configuration of this nucleus, at the high excitation energies reached in this reaction, can explain theoretically the measured alignments.

I. INTRODUCTION

The $^{12}C(h,p)^{14}N$ reaction mechanism has been considered many times, from low bombarding energies up to $E_h = 30$ MeV.[1-11] It is normally considered that for E_h below about 5 or 6 MeV, the compound-nucleus mechanism is predominant, while for E_h above about 10 MeV, it is generally thought that direct processes are most important. However, several authors have commented on the strong dependence of the cross sections with incident energy, and the presence, even at low energies, of certain stripping angular distributions. It is desirable, therefore, to measure, systematically with energy, parameters which will test more directly the mechanism by which the reaction proceeds. The determination of nuclear alignments, by the technique of angular-correlation measurements in geometry II of Litherland and Ferguson,[12] is a possible approach to this problem. This is particularly true for natural parity states, where the theoretical predictions are very different depending on the mechanism considered. In the present case of ^{14}N, as the electromagnetic properties of the final nucleus are known,[13] they appear as constants in the analysis of the angular correlations. Therefore, the angular correlations in the geometries $\theta_p = 0°$ and $\theta_p = 180°$ depend only on the population parameters $P(\gamma)$ for the magnetic substates $\gamma = 0$ and ± 1 which can be populated in ^{14}N. For the final level, characterized by total angular momentum J_f and projections γ, the $P(\gamma)$ depend only on the manner in which the level is formed.

In certain cases, the determination of the nuclear alignment for a given incident energy has enabled the dominant reaction mechanism to be deduced, but a systematic analysis as a function of incident energy and angle on the symmetry axis (0 and 180°) has not been reported. The use of this technique is especially interesting for nuclear reactions of the type $X(a,b)Y$, for $J_a + J_b \gg J_c$ where c is the transferred particle, i.e., $c = a - b$, such as $X(^6\text{Li},d)Y$ or $X(^7\text{Li},t)Y$, for example.[14] But even in the case of the reaction $^{12}C(h,p)^{14}N$, where this condition is not fulfilled $(J_a + J_b = J_c)$, the theoretical alignments can be very different according to the type of reaction considered.

In a preceding article,[9] we reported the analysis of the mechanism study of the reaction $^{12}C(h,p)^{14}N$, between incident energies of 4.6 to 11.0 MeV, by the measurement of excitation functions and proton angular distributions for the 10 bound states of ^{14}N. In addition, a study of the variation with energy of the p-γ angular correlation for the 7.03-MeV level, which γ decays principally to the ground state, showed strong fluctuations in the alignment of this state. Similar results have already been observed for this level,[15] as well as for the level at 5.10 MeV by Blake *et al.*[16] The purpose of this work is to extend the analysis formerly done for the single state at 7.03 MeV and $\theta_p = 180°$, to all bound states of ^{14}N. All the results have been analyzed within the framework of the direct-interaction theory, as well as the compound-nucleus theory.

II. EXPERIMENTAL PROCEDURE AND ANALYSIS

All the angular correlations were measured using the 6- and 4-MV Van de Graaff accelerators of the Strasbourg-Cronenbourg group of laboratories, using doubly ionized beams of helions. The ^{12}C targets were 100 to 120 $\mu g/cm^2$ thick, either self-supporting or deposited on silver or gold foils of thicknesses between 0.02 and 0.04 mm, depending on E_h for the measurements made with detection of particles at 0°. Generally the angular correlations were measured at three angles θ_γ, in two different experimental setups: (i) using three NaI(Tl) detectors at 90, 45, and 0°, each in coincidence with the annular particle detector at 180°; and (ii) using a moving NaI(Tl) detector in coincidence with an annular detector at 180° and a full detector at $\theta_p = 0°$.

Using the notation of Poletti and Warburton,[17] the theoretical expression for the angular-correlation function is

$$W(\theta) = \sum_{k_{\text{even}}} \rho_k(J_f) F_k(J_f J_f') Q_k P_k(\cos\theta)$$

$$= \sum_{k_{\text{even}}} a_{k_{\text{th.}}} P_k(\cos\theta).$$

The population parameters are solutions of the equations:

$$\sum_\gamma \rho_k(J_f,\gamma) P(\gamma) = a_{k_{\text{exp.}}} / F_k(J_f J_f') Q_k ,$$
$$\sum_\gamma P(\gamma) = 1 . \qquad (1)$$

The choice of only three angles to measure the angular correlations is justified by the fact that only the following transitions have been considered:

(i) For the J=1 levels at 6.21, 5.69, and 3.95 MeV, the strong branch to the level at 2.31 MeV.[18] $W(\theta)$ is in this case a linear function of $\cos^2\theta_\gamma$, and Eqs. (1) reduce to:

$$P(0) = -0.6873 a_2 + 0.3333 ,$$
$$P(1) = +0.3436 a_2 + 0.3333 . \qquad (2)$$

(ii) For the $J^\pi = 2^+$ level at 7.03 MeV, the almost 100% branch to the ground state. For the accurately known mixing ratio $\delta(E2/M1) = 0.637 \pm 0.028$,[9] the value of the experimental a_4 coefficient is very sensitive to the alignment of the level (Fig. 1).

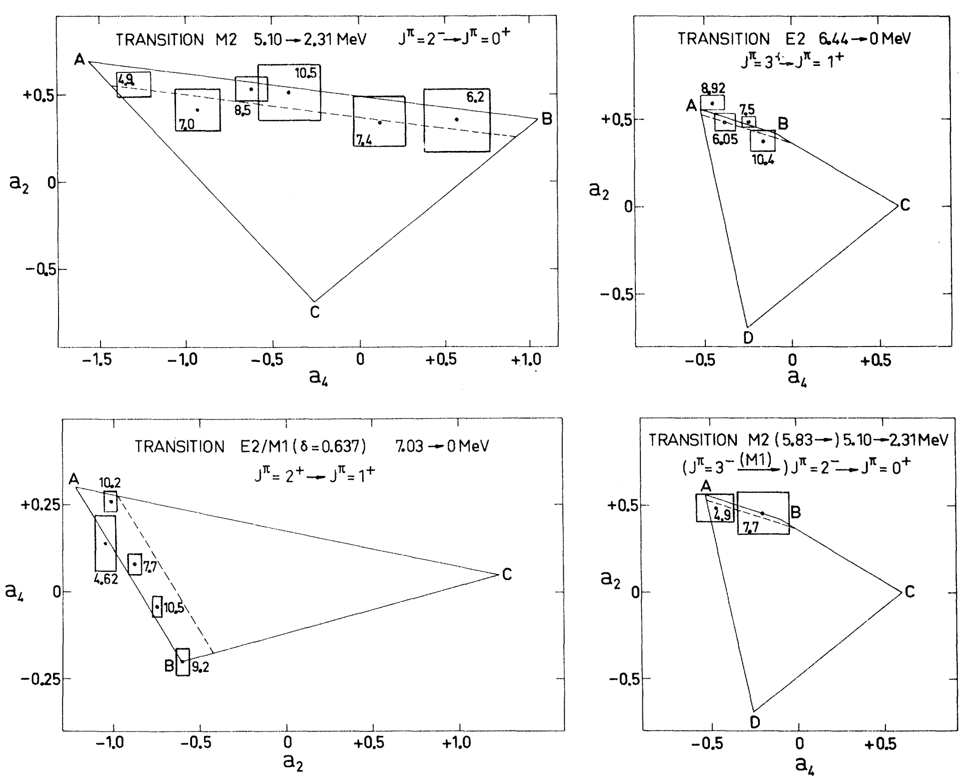

FIG. 1. Polygons bounding the possible theroetical values of the a_2 and a_4 angular-correlation coefficients for the indicated transitions. Points A, B, C, and D correspond to a total alignment in the $m = 0$, 1, 2, and 3 magnetic substates, respectively.

Equations (1) reduce to:

$$P(0) = -0.2327a_2 + 1.7132a_4 + 0.2000\,,$$
$$P(1) = -0.1164a_2 + 1.1421a_4 + 0.2000\,, \qquad (3)$$
$$P(2) = +0.2327a_2 + 0.2855a_4 + 0.2000\,.$$

(iii) For the $J^\pi = 2^-$ level at 5.10 MeV, only the pure M2 transition to the 2.31-MeV level. Even though the relative intensity of this branch is only 21%, the variation of the a_4 coefficient with the alignment is large (Fig. 1) and population parameters with acceptable precision could be obtained. Equations (1) reduce to:

$$P(0) = +0.4124a_2 - 0.3297a_4 + 0.2000\,,$$
$$P(1) = +0.2062a_2 + 0.2198a_4 + 0.2000\,, \qquad (4)$$
$$P(2) = -0.4124a_2 - 0.0549a_4 + 0.2000\,.$$

For the two $J = 3$ levels at 6.44 and 5.83 MeV, the angular correlations are not very sensitive to the alignment (Fig. 1). For this reason, no results are given here for these two levels. However, variations of the angular correlation with incident energy were observed.

In all the analyses of the angular correlations a possible population of the substates $|\gamma| \geq 2$ (for $J \geq 2$), due to the finite size effect of the particle counters, was taken into account. Experimentally, values of $P(2)$ were never found to exceed 10% of the total population. This is illustrated in Table IV of Ref. 9.

III. THEORETICAL ANALYSIS

The general expression for the angular-correlation function can be written[19]:

$$W = \sum_{J_f kK} \rho_{kK}(J_f J_f)\epsilon^*_{kK}(J_f J_f)\,,$$

where $\rho_{kK}(J_f J_f)$ and $\epsilon^*_{kK}(J_f J_f)$ are the statistical and efficiency tensors, respectively. It can be shown that the population factors $P(\gamma)$, which represent the probability of finding the final system in the state J_f with projections γ, can be written:

$$P(\gamma) = \langle J_f\gamma|\rho|J_f\gamma\rangle = \sum_k (-)^{J_f-\gamma}\langle J_f\gamma J_f - \gamma|k0\rangle\rho_{k0}(J_f J_f)\,,$$

where ρ is the density matrix of the discrete states $J_f(\gamma)$.

Two methods of calculating the alignments $P(\gamma)$ are possible. First, either the statistical tensors $\rho_{k0}(J_f J_f)$ necessary for the calculation of the function W can be determined and the $P(\gamma)$ deduced; or second, the elements of the density matrix $\langle J_f\gamma|\rho|J_f\gamma\rangle$ can be calculated directly.

Using the first of these methods, in the framework of the direct-interaction theory, Balamuth, Anastassiou, and Zurmuhle[20] have applied the statistical tensor calculations of Satchler[21] to the special case of collinear geometry and $J = 0$ targets. Assuming that spin-orbit coupling in the optical potentials in the entrance and exit channels is negligible, the following ratio is obtained:

$$\frac{P(1)}{P(0)} = \frac{\langle L0S1|J_f1\rangle^2}{\langle L0S0|J_f0\rangle^2}\,, \qquad (5)$$

if only a single L, S value for the orbital and intrinsic angular momenta of the pair of nucleons transferred contributes to populate a J_f state. This is the case for levels of natural parity. For levels of unnatural parity, two values of L can occur, and the alignments $P(\gamma)$ become a coherent sum over the allowed values L and L'. Then the predictions would also depend on the optical potentials used.

Using the first method also, we have calculated the alignments obtained with the compound-nucleus statistical theory.[22] The following relation is found, where the notation is the same as that of Sheldon and Strang[23]:

$$\rho_{\lambda 0}(J_f J_f) = \frac{1}{\rho_{00}(J_f J_f)} \sum_{\substack{J_i \mu\nu \\ l_1 j_1 l_2 j_2}} (-)^{j_2 - J_i}(2J_i+1)^2(2l_1+1)(2j_1+1)(2l_2+1)$$
$$\times (2j_2+1)(2\mu+1)^{1/2}(2\nu+1)^{1/2}\langle l_1 0\, l_1 0|\mu 0\rangle$$
$$\times \langle l_2 0\, l_2 0|\nu 0\rangle\langle \mu 0 \nu 0|\lambda 0\rangle W(j_1 j_1, J_i J_i;\, \mu J_0)$$
$$\times W(l_1 l_1, j_1 j_1;\, \mu s_1) W(l_2 l_2, j_2 j_2;\, \nu s_2) X(J_i J_i \mu;\, j_2 j_2 \nu;\, J_f J_f \lambda)\tau\,, \qquad (6)$$

and

$$P(\gamma) = \sum_\lambda (-)^{J_f-\gamma}\frac{1}{(2J_f+1)^{1/2}}\langle J_f\gamma J_f - \gamma|\lambda 0\rangle\rho_{\lambda 0}(J_f J_f)\,.$$

The indexes 1 and 2 correspond, respectively, to the incoming and outgoing particles and J_i is the angular momentum of the intermediate state of the compound nucleus ^{15}O. The penetrability term τ is related to the transmission coefficients T_{lj} as defined by Eq. 2.49 of Ref. 23. These quantities have been calculated using a standard optical-model code with the parameter values given in Ref. 22. All kinematically possible outgoing channels were taken into account,[22] in the calculation of the Hauser-Feshbach denominator formula (14 to 76 channels, from $E_h = 3$ to 11 MeV, respectively).

Using the second method, we have developed[22] the equations set up by Litherland and Ferguson.[12] By a suitable choice of coupling, a very simple relation is obtained:

$$\frac{P(1)}{P(0)} = \frac{\langle J_f 1 j_2 - \frac{1}{2} | J_i \frac{1}{2} \rangle^2}{\langle J_f 0 j_2 \frac{1}{2} | J_i \frac{1}{2} \rangle^2}, \tag{7}$$

valid only for the case of a resonant level J_i of ^{15}O which does not interfere with any other state, and with specific values for quantum numbers j_2 and l_2. This last condition corresponds to the assumption that the outgoing proton is in a well-defined orbit.

The theoretical predictions can be summarized as follows:

(i) If the reaction $^{12}C(h,p)^{14}N$ proceeds only by direct interaction, the alignments calculated (relation 5 and Table I) are independent of the bombarding energy, for a single value of the total orbital angular momentum transferred by the pair of nucleons. Following the Glendenning selection rule,[24] only a single ΔS, ΔT value is possible for double transfer reactions on $J=0$ target nucleus. It should also be pointed out that for such a reaction mechanism it is probably meaningful to compare only the experimental alignments measured at $\theta_p = 0°$ to these predictions. For the unnatural parity levels, the nonprevailing L values[7] have been bracketed in Table I. In addition, from the relation 5, the following conditions can be deduced:

(1) For the transfer of a quasideuteron $\Delta S = 0$, $\Delta T = 1$, the natural parity levels are completely aligned in the $\gamma = 0$ magnetic substate $[P(0) = 1]$. However, in ^{14}N, the only bound $T = 1$ state at 2.31 MeV has $J^\pi = 0^+$. It would be interesting to analyze the unbound level $J^\pi = 2^+$, $T = 1$ at 9.17 MeV, for which we have shown[15] that the γ decay competes with the particle decay in the ratio $\Gamma_p/\Gamma_\gamma = 10 \pm 3$. It was not possible to analyze the angular correlation of the 9.17 → 0 MeV transition (almost pure $M1$), this state being weakly excited by the (h,p) reaction. The analysis of a similar state $T = 1$, $J^\pi = 2^+$ at 1.59 MeV in ^{42}Sc has been done by Balamuth, Anastassiou, and Zurmuhle,[20] by the reaction

TABLE I. Theoretical alignments from the direct-interaction predictions for the 10 bound states of ^{14}N.

Level (MeV)	J^π	Transferred quantum numbers $L(L')$	S	T	Alignments $P(0)$	$P(1)$
0	1^+	2	1	0	0.67	0.17
		(0)			(0.33)	(0.33)
2.31	0^+	0	0	1	1.00	···
3.95	1^+	0	1	0	0.33	0.33
		(2)			(0.67)	(0.17)
4.91	0^-	1	1	0	1.00	···
5.10	2^-	1	1	0	0.40	0.30
		(3)			(0.60)	(0.20)
5.69	1^-	1	1	0	0.00	0.50
5.83	3^-	3	1	0	0.00	0.50
6.21	1^+	0	1	0	0.33	0.33
		(2)			(0.67)	(0.17)
6.44	3^+	2	1	0	0.43	0.29
		(4)			(0.57)	(0.21)
7.03	2^+	2	1	0	0.00	0.50

TABLE II. Alignment $P(0)$ calculated from the compound nuclear theory as a function of value of the angular momentum of the final state of the resonance and of the outgoing proton.

J_f (^{14}N)	J_i (^{15}O)	Alignment $P(0)$ Total angular momentum of the outgoing proton $\frac{1}{2}$	$\frac{3}{2}$	$\frac{5}{2}$	$\frac{7}{2}$	$\frac{9}{2}$	$\frac{11}{2}$
1	$\frac{1}{2}$	0.33	0.67				
	$\frac{3}{2}$	0.67	0.11	0.67			
	$\frac{5}{2}$		0.67	0.05	0.67		
	$\frac{7}{2}$			0.67	0.03	0.67	
2	$\frac{1}{2}$		0.40	0.60			
	$\frac{3}{2}$	0.40	1.00	0.19	0.60		
	$\frac{5}{2}$	0.60	0.19	1.00	0.11	0.60	
	$\frac{7}{2}$		0.60	0.11	1.00	0.07	0.60
	$\frac{9}{4}$			0.60	0.07	1.00	0.05
3	$\frac{1}{2}$			0.43	0.57		
	$\frac{3}{2}$		0.43	0.92	0.25	0.57	
	$\frac{5}{2}$	0.43	0.92	0.25	0.92	0.16	0.57
	$\frac{7}{2}$	0.57	0.25	0.92	0.16	0.92	0.11
	$\frac{9}{2}$		0.57	0.16	0.92	0.11	0.92
	$\frac{11}{2}$			0.57	0.11	0.92	0.08

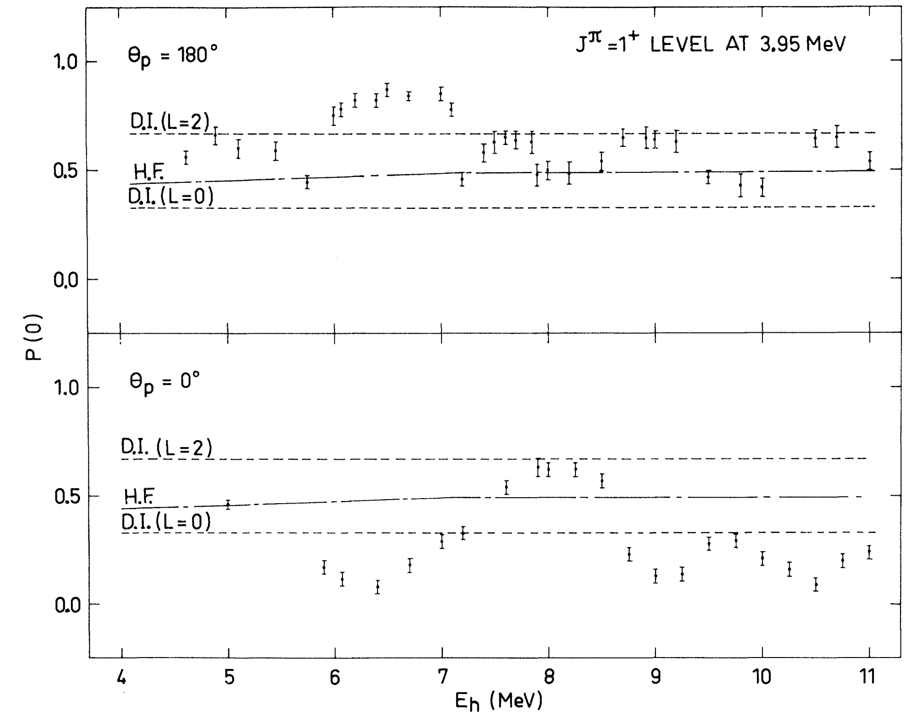

FIG. 2. Experimental variations of the alignment of the 3.95-MeV level, in the magnetic substate $\gamma=0$, as a function of incident energy for $\theta_p=180$ and 0°. The corresponding theoretical predictions of the DI theory and the statistical model of HF are also shown.

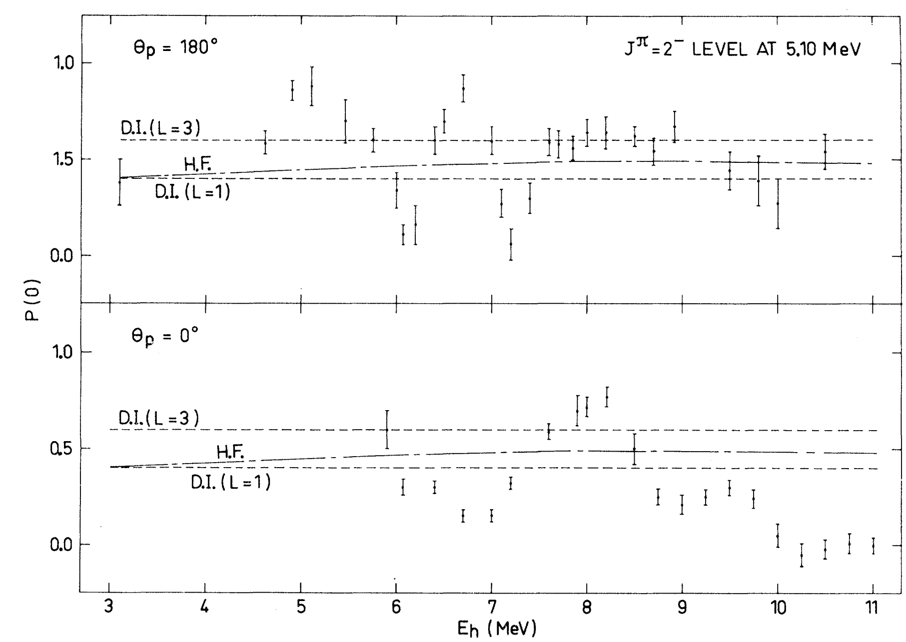

FIG. 3. Experimental variations of the alignment of the 5.10-MeV level, in the magnetic substate $\gamma=0$, as a function of incident energy for $\theta_p=180$ and 0°. The corresponding theoretical predictions of the DI theory and the statistical model of HF are also shown.

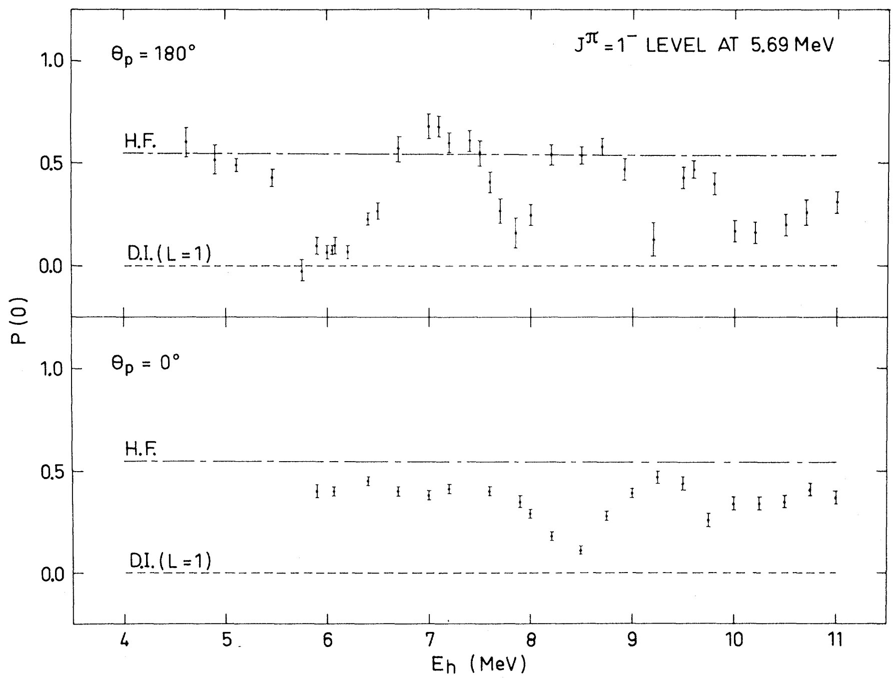

FIG. 4. Experimental variations of the alignment of the 5.69-MeV level, in the magnetic substate $\gamma = 0$, as a function of incident energy for $\theta_p = 180$ and 0°. The corresponding theoretical predictions of the DI theory and the statistical model of HF are also shown.

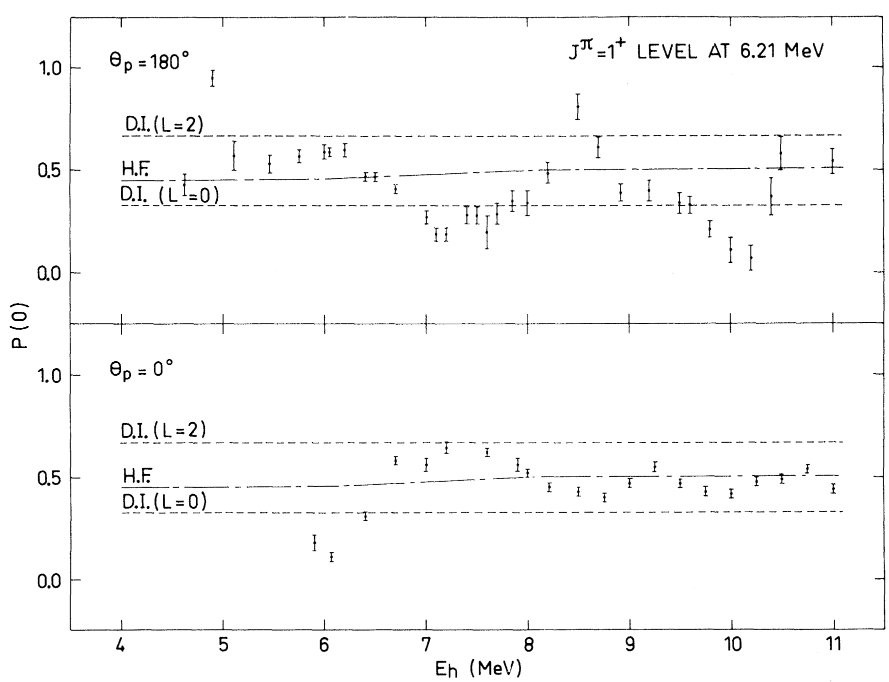

FIG. 5. Experimental variations of the alignment of the 6.21-MeV level, in the magnetic substate $\gamma = 0$, as a function of incident energy for $\theta_p = 180$ and 0°. The corresponding theoretical predictions of the DI theory and the statistical model of HF are also shown.

$^{40}Ca(h, p)^{42}Sc$, with the result $P(0) = 0.95 \pm 0.06$ at $E_h = 15$ MeV.

(2) The transfer of a quasideuteron is impossible for states of unnatural parity. In fact, the $T = 1$ levels at 8.71 MeV ($J^\pi = 0^-$), 12.72 MeV ($J^\pi = 1^+$), and 9.508 MeV ($J^\pi = 2^-$), are not observed by the reaction $^{12}C(h, p)^{14}N$ (Ref. 7).

(3) For the transfer of a deuteron $\Delta S = 1$, $\Delta T = 0$, the levels of natural parity are all aligned in $|\gamma| = 1$. That is $P(0) = 0$ and $P(+1) = P(-1) = 0.5$. States which correspond to this case are those at 5.69 MeV ($J^\pi = 1^-$), 7.03 MeV ($J^\pi = 2^+$), and at 5.83 MeV ($J^\pi = 3^-$).

(4) For the transfer of a deuteron the alignments of the unnatural parity states depend on the transferred L. The corresponding values are given in Table I for the levels at 3.95 and at 6.21 MeV (both $J^\pi = 1^+$), at 5.10 MeV ($J^\pi = 2^-$), and at 6.44 MeV ($J^\pi = 3^+$).

(ii) If the reaction $^{12}C(h, p)^{14}N$ proceeds only by the formation of the compound nucleus ^{15}O, with a large overlapping of the states at the excitation energies reached, (statistical theory of Hauser-Feshbach[25]) then the alignment of the final levels are practically constant with bombarding energy (relation 6). It is found that $0.40 \leq P(0) \leq 0.55$ regardless of the final level.

(iii) If the reaction $^{12}C(h, p)^{14}N$ proceeds only by the formation of the compound nucleus ^{15}O, in which a single resonant state J_i contributes at a given incident energy to the formation of state J_f of ^{14}N, then the corresponding alignment can vary strongly from one energy to another, depending on the values of J_i and j_2 (relation 7 and Table II).

IV. RESULTS AND DISCUSSION

Figures 2 to 6 present the alignments, obtained for the levels at 3.95, 5.10, 5.69, 6.21, and 7.03 MeV, respectively, in the $m = 0$ magnetic substate, for $\theta_p = 0$ and 180°. Neither the direct-interaction (DI) theory, nor the compound nuclear process (Hauser-Feshbach theory: HF), which have both been used to fit previously measured angular distributions,[9] shows sufficiently good agreement with the data, that the dominance of one or the other of these mechanisms can be said to be clearly demonstrated.[22] However, it is interesting to consider the total cross section, summed over all the levels from 3.95 to 7.03 MeV obtained previously, and summarized in Fig. 21 of Ref. 9. These are the levels for which we have complete results. The resulting curve is compared with the corresponding theoretical predictions (HF and DI) in Fig. 7.

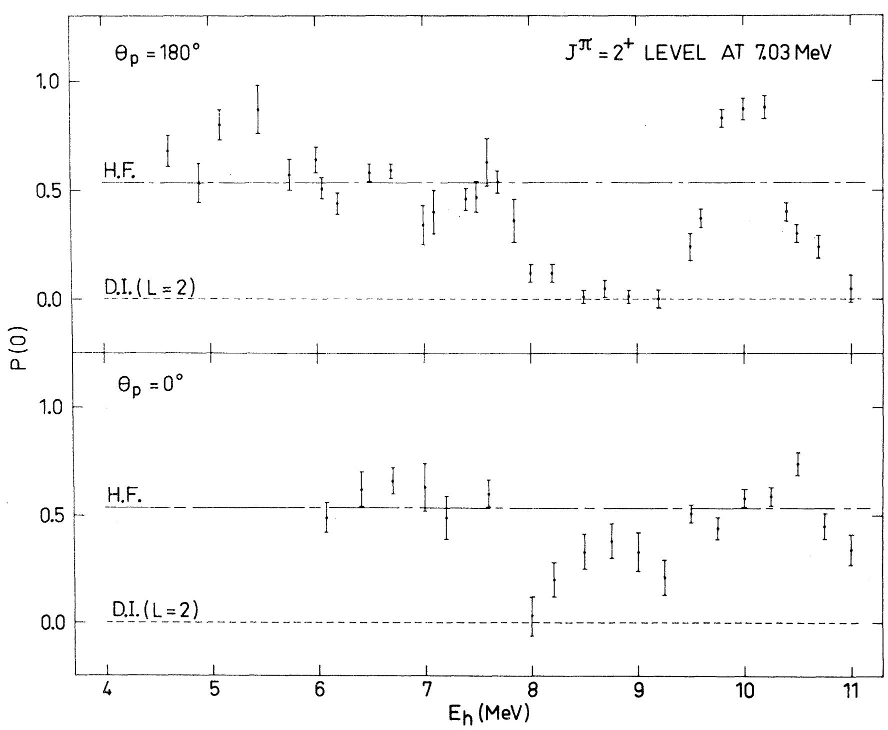

FIG. 6. Experimental variations of the alignment of the 7.03-MeV level, in the magnetic substate $\gamma = 0$, as a function of incident energy for $\theta_p = 180$ and 0°. The corresponding theoretical predictions of the DI theory and the statistical model of HF are also shown.

The values of the DI curve are relative,[26] and only the form should be considered. Several conclusions can be drawn from this figure. In general, for $5 \leq E_h \leq 11$ MeV, the reaction proceeds by formation of the compound nucleus ^{15}O. The average slope of the experimental curve agrees with the HF predictions, showing no evidence that the DI becomes dominant before 11 MeV. Finally, an important resonant structure is superimposed on a statistical theory background. These resonances are centered around energies of 6.5, 7.2, 8.1, and 10.0 MeV. But the precision of these values is quite poor, considering that only a small number of experimental points is available. On the other hand, the energies of the resonances in the individual total excitation functions (Fig. 21 of Ref. 9), typically with a width of 500 keV, do not correspond exactly so that in the sum curve they are partially washed out. An example is the single point for the resonance at $E_h \simeq 10$ MeV (Fig. 7), this resonance being apparent in six of the eight individual excitation functions. These resonances can be explained by resonant capture phenomena in the two channels considered, i.e., $^{12}C+h$ and $^{14}N+p$, corresponding to quasigiant resonances in ^{15}O.

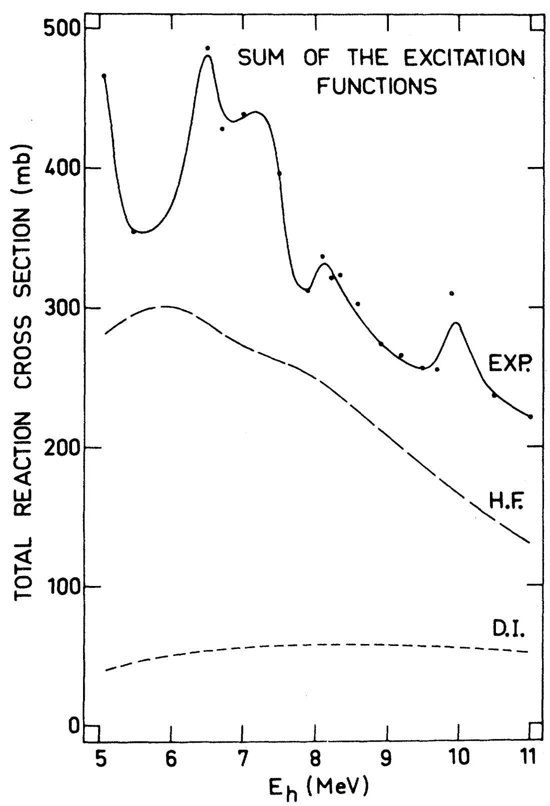

FIG. 7. Sum of the experimental and theoretical excitation functions for all the bound levels of ^{14}N from 3.95 to 7.03 MeV. The scale for the DI curve is relative.

In this regard, the experimental data of Fig. 7 can be compared with the results obtained by Weller and Van Rinsvelt[27] for the elastic scattering of helions on ^{12}C for $4.4 \leq E_h \leq 8.2$ MeV and $\theta_h = 140°$. A correspondence can be seen between their results and our measurements, in the range 6 to 8 MeV. In the outgoing α-particle channel, a structure was also seen by these authors in the differential and total cross sections, similar to that observed in the elastic scattering. This result led them to describe ^{15}O as a particle coupled to a ^{11}C core (α-particle core-excited threshold states), for excitation energies between 14 and 19 MeV. This model has been considered in more detail recently.[28-30] In the present work we should observe, rather, states corresponding to a proton coupled to a ^{14}N core. All the outgoing channels of the $^{12}C+h$ reaction show resonant structure: $^{12}C+h$ (Ref. 27), $^{14}O+n$ (Ref. 31), and $^{11}C+\alpha$ (Ref. 27). However, for a given incident energy, the exact correspondence between the resonances is difficult, even dangerous, to specify, since in each channel a certain number of strongly overlapping states of very different configurations can contribute.

The presence of resonances in the outgoing channel $^{14}N+p$ is supported by the giant-dipole-resonance results obtained by Kuan *et al.*[32] These authors have studied the dipole transitions to the ground state of ^{15}O, by the reaction $^{14}N(p\gamma)^{15}O$, for incident energies corresponding to excitation energies between 9 and 25 MeV in ^{15}O. All the energies we used are in the zone $E_x = 14$ to 21 MeV, where the giant resonance of ^{15}O is strongly structured as can be seen in the excitation curve of Fig. 7, Ref. 32. In particular we note that for $6 \leq E_h \leq 8$ MeV ($16.8 \leq E_x \leq 18.5$ MeV), a minimum occurs in this curve, though we have seen a resonance at the same energies in the incoming channel (Fig. 7).

Among the similarities between our results (Ref. 9 and Fig. 7) and those of Kuan *et al.*,[32] the most striking is for the level of very pure configuration at 7.03 MeV. This suggests a corresponding ($p \otimes {}^{14}N^*$, $J^\pi = 2^+$) description of ^{15}O at the excitation energies considered. Though only a ($p \otimes {}^{14}N$, ground state) configuration of the states excited in ^{15}O by radiative capture can be considered, we note the similarities between the wave functions obtained by Lie[33] for the ground, 2.31-, 3.95-, and 7.03-MeV states. These four levels are essentially two hole states, with only a little contribution of two-particle–four-hole configuration. However, such a model should be applied cautiously, since a strong and very large resonance ($E_p = 9.85$ MeV, $\Gamma = 600 \pm 100$ keV) exists[34] in the ^{14}N-

$(p,n)^{14}O$ reaction. There is also the possibility of others of a similar nature corresponding to E_h $=5.5$, 6.0, 7.2, and 8.1 MeV. In addition, proton elastic and inelastic scattering studies on ^{14}N by Oda *et al.*,[35] indicate a predominant compound-nucleus reaction mechanism, and a resonance structure for the $(p_{3/2}, p_{1/2})^{-1}$ states (levels at 3.95 and 7.03 MeV) was found at energies corresponding approximately to those reported by Kuan *et al.*[32]

The population factors $P(0)$, given in Table II, are based on the assumption of isolated intermediate states, which is certainly not the case here, except when we deal with quasigiant resonances in ^{15}O which do not interfere with each other. In general, the presence of many overlapping resonances, which in Fig. 7 appear to make up a large part of the total cross section, will average out the final state alignments, according to Eqs. (6). Superimposed on this background of states, a level which dominates due to its $(p \otimes {}^{14}N)$ configuration, will be responsible for the measured alignment. Mathematically, this corresponds to the inclusion of a weight, or an intensity factor $\alpha(J_i)$, to the relations which give the population factors.[9]

Considering our results, it seems that the observed fluctuations cannot be explained by an increasing importance of the DI mechanism with incident energy. This extreme model of the direct transfer of two nucleons, whose cross section remains approximately constant with bombarding energy (Fig. 7, DI curve), should contribute most clearly in the valleys of the total cross-section curve. The total alignment of the 7.03-MeV level in the $|m|=1$ substates, around $E_h=9$ MeV, can serve as an illustration (Fig. 6, Table I). If, in a general way, the proton angular distributions agree better with the DI predictions above $E_h=8$ MeV, the corresponding $P(0)$ alignments do not support them.

A complete quantitative study would require a knowledge of the structure of ^{15}O. From the theoretical point of view, the configurations of ^{15}O states at these excitation energies could be obtained in three ways:

(i) From a weak coupling model calculation, Lie, Engeland, and Dahll[36,37] have obtained excellent agreement with the experimental levels up to 13 MeV. But to obtain energy levels up to 21 MeV would require a considerable increase in the configuration space.[38]

(ii) From statistical phenomenon of the Ericson type, which can be applied to observation of structure in a region where many compound levels are present.[39] However, the uncertainties due to the limited energy range over which the data were collected are likely to be large in the present case.

(iii) From qualitative estimates of where the levels obtained by coupling a proton in the $d_{5/2}$, $s_{1/2}$, and $d_{3/2}$ orbits to a ^{14}N core should be found in ^{15}O. Using the model of Baz and Manko,[40] as applied by Weller,[28] such states should occur at excitation energies of 9.55 and 16.58 MeV in ^{15}O for the ground and the 7.03-MeV states of ^{14}N, respectively. Since their calculations were based on a very simple model, the presence of such states in the region of excitation considered is still quite possible.

V. CONCLUSION

This work has permitted us to show that for incident energies up to 11 MeV, the $^{12}C(h,p)^{14}N$ reaction proceeds predominantly through the compound-nucleus mechanism. The structure of ^{15}O, at the high excitation energies reached $(14.4 \leq E_x \leq 20.9$ MeV), is probably responsible for all the fluctuations observed. The data contain implicitly some information on the excited states of ^{15}O, but it is not possible to extract it in a usable form. The contribution of a direct or semidirect[41] process seems to be appreciable only in the valleys of the excitation curves for $E_h \gtrsim 8$ MeV.

The systematic use of the technique of angular correlations in collinear geometry has been shown to be a useful tool to investigate the mechanism of a nuclear reaction. It has enabled us to rule out the predominance of the DI mechanism at low energies, where some proton angular distributions show typical stripping patterns. Such shapes could be explained by the interference between two resonances, for example, using the relations given by Blatt and Biedenharn.[42]

The alignment fluctuations observed for all the bound levels of ^{14}N, either for $\theta_p=0$ or $180°$, are certainly not an exclusive characteristic of the $^{12}C(h,p)^{14}N$ reaction. It is known that similar phenomena are also present in other reactions, such as $^{16}O(h,p)^{18}F$ (Ref. 43) or $^{40}Ca(h,p)^{42}Sc$ (Ref. 20), for example. A study, similar to that presented here for a large range of incident energies, would allow a better understanding of these reaction mechanisms which are difficult to deduce clearly from only the excitation functions and particle angular distributions. In addition, the extension of the present study of the $^{12}C(h,p)^{14}N$ reaction, up to $E_h \sim 20$ MeV, would test the validity of the DI process, shown to be predominant at $E_h=13.9$,[3] 15,[10] 20.1,[7] and 25.3 MeV.[8] Experiments of this nature are planned in our laboratory.

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