$^{12}C(^6Li,d)^{16}O \to \alpha + ^{12}C$ reaction mechanism by means of angular correlation measurements

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The particle-particle angular correlation method is applied to the reaction $^{12}C(^6Li,d)^{16}O \to \alpha + ^{12}C$. Deuterons were detected at $\theta_d^{lab} = 10°$. Information on the reaction mechanism is obtained by analyzing the shape and the angular shift of the experimental data. A dominant direct transfer mechanism is found for the primary reaction. The ratios Γ_{α_0}/Γ and the α-reduced widths γ_{α_0} are deduced.

[NUCLEAR REACTIONS $^{12}C(^6Li,d)^{16}O \to \alpha + ^{12}C$. $E_{^6Li} = 34$ MeV; measured $W(\Omega_d, \Omega_\alpha)$; confirmed J^π for ^{16}O levels. Evaluated Γ_{α_0}/Γ and γ_{α_0}. EFR-DWBA and HF analysis.]

I. INTRODUCTION

It has been shown[1-3] that the measurement of the particle-particle angular correlation $X(a,b)Y^*_{I'} \to c + Z$ gives information on the properties of the residual nucleus levels and on the mechanism of the primary reaction $X(a,b)Y^*_{I'}$.

The sensitivity of the correlation curve to the reaction mechanism is particularly evident when the ejectile b is detected at an angle θ_b different from zero. The evolution of the correlation curve with increasing θ_b has been recently discussed under different hypotheses on the primary reaction mechanism.[1,2] For small θ_b values the shape of the whole correlation is similar to that obtained at $\theta_b = 0°$, the curve being only shifted by an angular amount δ that depends on the relative population of the magnetic substates $m_{I'}$.[1] In general, different reaction mechanisms produce different values of the populations $P_{m_{I'}}$ and, in turn, different angular shifts.

In a recent work[4] we measured the angular distributions of the deuterons emitted in the $^{12}C(^6Li,d)^{16}O$ reaction at incident energies of 28 and 34 MeV. The analysis of the data has shown that this reaction can be understood as due mainly to a direct α-transfer mechanism for the transitions leading to the ^{16}O states belonging to the rotational band $K^\pi = 0^+$ [6.05 MeV(0^+), 6.92 MeV (2^+), 10.35 MeV (4^+), and 16.3 MeV (6^+)] and to the 7.11 MeV (1^-) and the 6.13 MeV (3^-) ^{16}O levels. This result agrees with that found in two similar investigations: the first one on the same reaction done at higher incident energy[5] and the other on the $^{12}C(^6Li,t)^{16}O$ at 38 MeV.[6]

We have also recently measured[2] the $^{12}C(^6Li,d)^{16}O \to \alpha + ^{12}C$ angular correlation between deuterons and α particles at $\theta_d = 0°$ and at $E_{^6Li} = 34$ MeV. In this selected geometry the correlation curve is symmetric with respect to 90°,[7] allowing an accurate determination of the spin and parity of the involved level. This method has been also applied to the $^{12}C(^{12}C,^8Be)^{16}O \to \alpha + ^{12}C$ reaction successfully.[8] However, as mentioned before, information on the reaction mechanism is better gained if a noncollinear geometry is adopted. Then, in the present work, we have extended the previous measurements of the $^{12}C(^6Li,d)^{16}O \to \alpha + ^{12}C$ reaction by detecting the emitted deuterons at $\theta_d = 10°$. Data on this reaction have been carried out previously by Artemov *et al.*[3] at lower energy, reporting only the high energy ^{16}O states.

We have analyzed our experimental results in terms of exact finite range-distorted wave Born approximation (EFR-DWBA) and compound nucleus mechanism.

Section II of the present work concerns the experimental procedure. Section III is devoted to the analysis of the data in terms of the formalism developed by Da Silveira.[1] Some conclusions are drawn in Sec. IV.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A 34 MeV $^6Li^{+++}$ beam was produced by the CEN-Saclay FN tandem Van de Graaff with intensity of the order of 65 nA. The target used was a self-supporting natural C foil, 150 ± 20 $\mu g/cm^2$ thick.

The emitted deuterons and the α particles in coincidence were detected by means of two ΔE-E

silicon counter telescopes: $\Delta E_d = 206$ μm, $E_d = 3000$ μm; $\Delta E_\alpha = 13.8$ μm, $E_\alpha = 300$ μm. The particles were identified by an analogical processing of the E and ΔE signals. The elementary information corresponding to identification, total energy, and time were stored on magnetic tape for off-line analysis. The overall deuteron energy resolution [full width at half maximum (FWHM)] was about 100 keV, the time resolution about 8 ns.

The deuterons were detected at $\theta_d = 10°$ ($\phi_d = 0$ azimuthal angle) and angular correlations were obtained in the angular range $35° \leq \theta \leq 95°$ ($\phi_\alpha = \pi$ azimuthal angle) in steps of 2.5°.

A single deuteron spectrum is displayed in Fig. 1; the arrows indicate the ^{16}O levels for which the d-α correlation measurements were carried out.

Figure 2 shows a two-dimensional energy spectrum of d-α coincidences obtained at $\theta^{lab} = 65°$. An interesting feature of this spectrum is the presence of a strong component due to the particles corresponding to the first excited 4.43 MeV (2^+) and to the 9.6 MeV (3^-) ^{12}C levels.

Figure 3 shows the deuteron energy spectra in coincidence with α_0 particles and with the α_1 particles. It can be observed from Figs. 2 and 3 that an important contribution to the broad structure observed in the single deuteron spectrum comes from deuterons associated with alpha particles corresponding to excited states of the ^{12}C final nucleus. Then, as already proposed in Ref. 9, the continuous deuteron spectrum cannot be interpreted as due only to a ^{6}Li breakup mechanism leaving the target nucleus in its ground state.

The experimental d-α angular correlations for α particles corresponding to the decay to the ^{12}C g.s. are shown in Fig. 5.

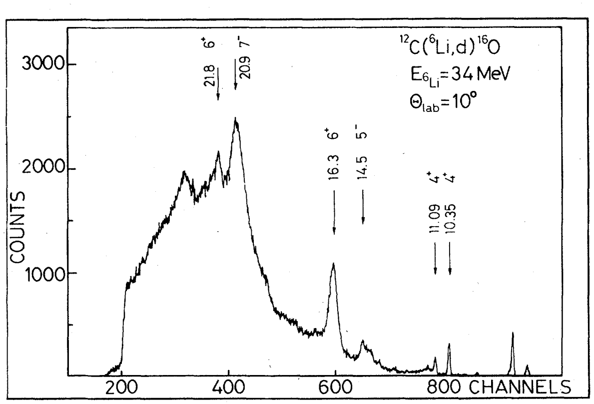

FIG. 1. Deuteron energy spectrum from the ^{6}Li induced reaction on ^{12}C.

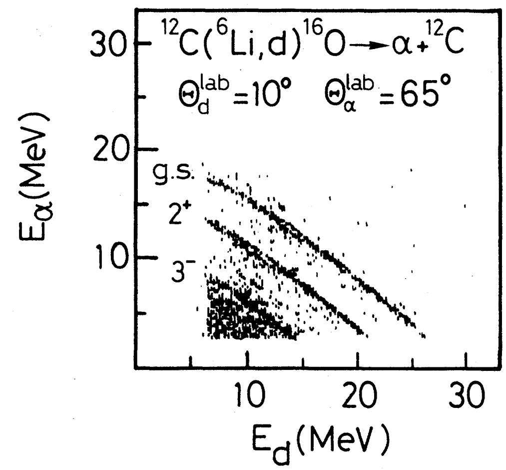

FIG. 2. Two-dimensional energy spectrum of d-α coincidences from the ^{12}C(^{6}Li, d) ^{16}O$\rightarrow \alpha + ^{12}$C reaction. Note that a large amount of d-α coincidence events are distributed along kinematic bands corresponding to the excited 4.43 MeV (2^+), 9.6 MeV (3^-) ^{12}C levels.

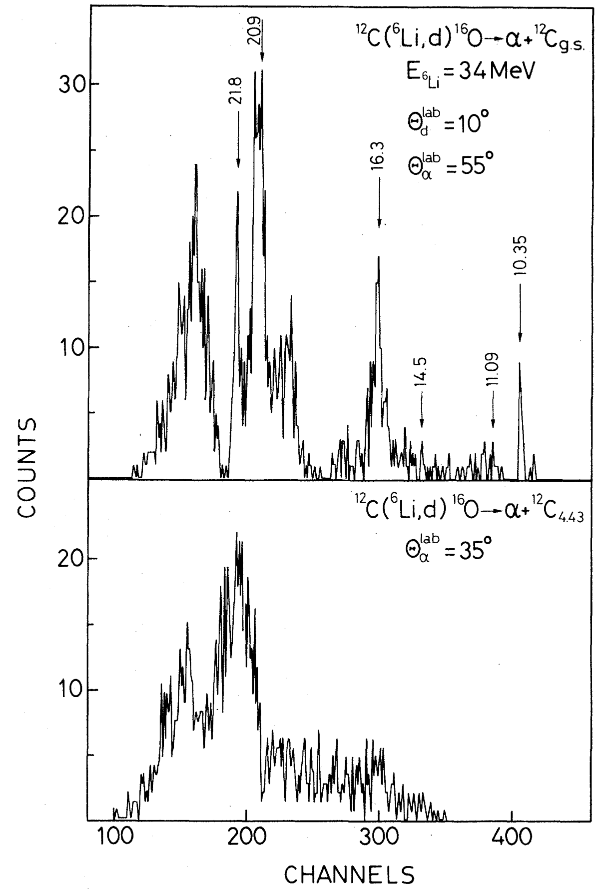

FIG. 3. Coincidence spectra from the ^{12}C(^{6}Li, d) ^{16}O $\rightarrow \alpha + ^{12}$C reaction obtained from projecting the events distributed in the ground state locus or in the 4.43 MeV (2^+) locus onto the deuteron energy axis.

III. ANALYSIS OF THE DATA

A. Reaction mechanism

The theoretical expression of the correlation function, when the formation of a well-defined state is assumed, is[1]

$$W(\Omega_1,\Omega_2)=N\sum_{\substack{m_i m_I\\ m_{i''}m_{I''}}}\left|\sum_{m_{I'}}[T^{m_i m_I}_{m_{i'}m_{I'}}(\Omega_1)T'^{m_{I'}}_{m_{i''}m_{I''}}(\Omega_2)]\right|^2, \quad (1)$$

where $T(\Omega_1)$ and $T'(\Omega_2)$ are the transition amplitudes of the primary reaction and of the disintegration process, respectively. For other notations see Refs. 1 and 2.

In the channel spin representation and in the case of the $^{12}C(^6Li,d)^{16}O \to \alpha + ^{12}C$ reaction ($I=0$ then $s=I$, $i''=0$ then $s''=I''$) the expansions in partial waves for the reaction and disintegration amplitudes are[1]

$$T^{m_i}_{m_{i'}m_{I'}}(\Omega_1)=\sum_{s'm_{s'}}\sum_{\substack{Jll'\\ m_J m_{l'}}}(2l+1)^{1/2}(ls\,0\,m_s|Jm_J)\times(l's'm_{l'}m_{s'}|Jm_J)(I'i'm_{I'}m_{i'}|s'm_{s'})\times S^J_{\substack{s'l'\\ sl}}Y^{m_{l'}}_{l'}(\Omega_1)$$

and

$$T'^{m_{I'}}_{m_{I''}}(\Omega_2)=\sum_{l''m_{l''}}(l''I''m_{l''}m_{I''}|I'm_{I'})S^{I'}_{I''l''}Y^{m_{l''}}_{l''}(\Omega_2),$$

where the information on the reaction and disintegration mechanism is contained in the matrix elements $S^J_{s'l'sl}$ and $S^{I'}_{I''l''}$, respectively.

The normalization condition $\int_{4\pi}W(\Omega_1,\Omega_2)d\Omega_2=1$ defines

$$N^{-1}=\sum_{\substack{m_i m_I\\ m_{i'}m_{I'}}}|T^{m_i m_I}_{m_{i'}m_{I'}}(\Omega_1)|^2\sum_{s''l''}\left|S^{I'}_{\alpha''l''s''}\right|^2.$$

Then, expression (1) becomes

$$W(\Omega_1,\Omega_2)=\frac{\displaystyle\sum_{\substack{m_i m_{i'}\\ m_{I''}}}\left|\sum_{m_{I'}}T^{m_i}_{m_{i'}m_{I'}}(\Omega_1)T'^{m_{I'}}_{m_{I''}}(\Omega_2)\right|^2}{\displaystyle\sum_{\substack{m_i m_{i'}\\ m_{I'}}}\left|T^{m_i}_{m_{I'}m_{i'}}(\Omega_1)\right|^2\sum_{l''}\left|S^{I'}_{I''l''}\right|^2}. \quad (2)$$

The decay amplitude $S^{I'}_{I''l''}$ is related to the total level width $\Gamma^{I'}$ and to the partial width $\Gamma^{I'}_{I''l''}$ for the decay into the channel $(I'l''I'')$ by

$$|S^{I'}_{I''l''}|^2=\Gamma^{I'}_{I''l''}/\Gamma^{I'}.$$

Thus the differential cross section for the sequential process can be expressed in the form

$$\frac{d^2\sigma(\Omega_1,\Omega_2)}{d\Omega_1 d\Omega_2}=\frac{d\sigma(\Omega_1)}{d\Omega_1}\frac{\sum_{l''}\Gamma^{I'}_{I''l''}}{\Gamma^{I'}}W(\Omega_1,\Omega_2). \quad (3)$$

We calculated the amplitudes $T^{m_i}_{m_{i'}m_{I'}}(\Omega_1)$ in the framework of the EFR-DWBA using the code SATURN-MARS-I of Tamura and Low,[10] assuming that the primary process is a direct α transfer without spin-orbit interaction. These amplitudes have also been calculated, in the hypothesis of a compound nucleus statistical mechanism, using the Hauser-Feshbach (HF) formalism.[1,11]

The optical model parameters for DWBA and HF calculations reported in Tables I and II, respectively, are the same as those in Ref. 4. Finally, the complete calculation of expression (2) has been carried out, for both the assumed reaction mechanisms, using the CORRELA code of Da Silveira.[12]

As an example, the theoretical DWBA and HF correlation curves for the 21.8 MeV (6^+) ^{16}O level are shown together with the experimental data in Fig. 4 as solid and dashed lines, respectively. We note that the angular shift and the positions of the maxima and minima predicted by both the HF and DWBA calculations reproduce the data. However, the strongly oscillating behavior of the experimental angular correlation is very well accounted for by the DWBA curve. This finding and the very smooth behavior of the HF curve indicate that the contribution from the statistical mechanism is negligible. Similar results have been found for all the transitions investigated in this work.

Therefore only the DWBA calculations are shown, as solid lines, in Fig. 5 together with the experimental data. The spins and parities of ^{16}O levels at 10.35 MeV (4^+), 16.3 MeV (6^+), 14.5

TABLE I. Optical model parameters for EFR-DWBA calculations.

Channel	V[a]	r_v	a_v	W	r_w	a_w	r_c	Ref.
$^6Li+^{12}C$	250	1.354	0.65	30[b]	1.354	0.65	2.0	17,18
$d+^{16}O$	95	1.127	0.8	10[b]	1.332	0.8	2.0	
d-α		1.545[c]	0.65				1.545[c]	17
^{12}C-α		1.25[c]	0.65				1.25[c]	

[a] Form factor: Woods-Saxon.
[b] Form factor: Woods-Saxon derivative.
[c] $R=r(A_1^{1/3}+A_2^{1/3})$.

TABLE II. Optical model parameters for HF calculations. Potential depths are in MeV, lengths in fm, and the radii dependence is $R = rA_t^{1/3}$. For the spin-orbit potential the same radius and diffuseness were used as in the real part.

Channel	V^a	r_v	a_v	W	r_w	a_w	r_c	$V_{so}{}^b$	Ref.
$^6Li+^{12}C$	241	1.75	0.55	14.5^a	2.27	0.23	2.5		19
$n+^{17}F$	c	1.309	0.66	b, e	1.26	0.48	1.309		20
$p+^{17}O$	d	1.25	0.65	7.70^b	1.25	0.47	1.25	7.5	21
$d+^{16}O$	101.4	1.0	0.717	8.75^b	1.589	0.625	1.3		22
$t+^{15}O$	146.8	1.4	0.551	18.4^a	1.4	0.551	1.3		23
$\alpha+^{14}N$	195	1.28	0.654	21^a	1.28	0.654	1.3		24

[a] Form factors: Saxon-Woods.
[b] Form factors: Saxon-Woods derivative.
[c] Energy dependence: $V(E) = 47.01 - 0.267\,E - 0.00118\,E^2$.
[d] Energy dependence: $V(E) = 56.1 - 0.55\,E$.
[e] Energy dependence: $W(E) = 9.52 - 0.53\,E$.

MeV (5^-), 20.9 MeV (7^-), and 21.8 MeV (6^+), previously assigned,[2,13] are confirmed. We note that both the shapes and the angular shifts are well reproduced, definitively confirming that all the above levels are populated mainly through a direct α transfer.

These levels, except the 21.8 MeV, have been also analyzed in Ref. 8, in which the $^{12}C(^{12}C,^8Be)^{16}O \to \alpha + ^{12}C$ reaction was studied. A good consistency is generally found between the two results. In effect, the energy resolutions obtained in the two cases are quite different (FWHM ~ 400 keV in that reaction) and hamper any detailed comparison, particularly at high excitation energy. However, some important differences can be remarked. In the $^{12}C(^{12}C,^8Be\alpha)^{12}C$ reaction the 11.09 MeV (4^+) level is only noticeable and the 21.8 MeV (6^+) level is only seen in the α_1 decay. On the other hand, a possible 8^+ state is reported at 22.5 ± 0.5 MeV, for which, up to now, no clear evidence is found in our case. These differences probably originate from the different selectivities shown by the two (^{6}Li,d), (^{12}C,^{8}Be) primary reactions in the population of the α-decaying states.

In Fig. 4 a comparison for the 21.8 MeV level is made between the present results and the previous ones obtained at $\theta_d = 0°$.[2] It is evident that the correlation curve has the shape substantially unchanged but it is only shifted.

We note that, for small θ_d values, the angular shift has the following simplified expression[1]:

$$\delta \simeq \frac{2}{l'}\left(\frac{P_1(\Omega_1)}{P_0(\Omega_1)}\right)^{1/2}\cos\xi\,,$$

where ξ is the relative phase between the amplitudes corresponding to $m=0$ and $m=1$, and $P_0(\Omega_1)$,

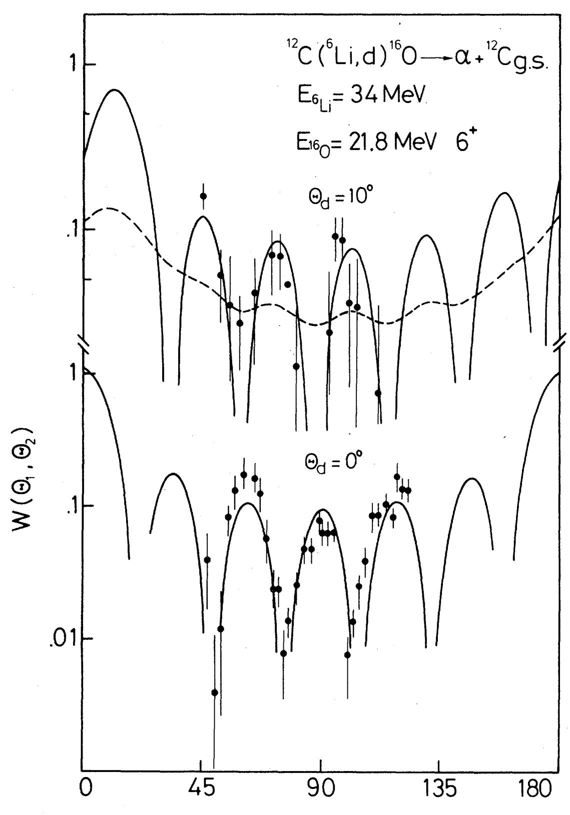

FIG. 4. Comparison of the $\theta_d = 0°$ and $\theta_d = 10°$ results of the d-α correlation function for the 21.8 MeV (6^+) ^{16}O level. Solid lines are the results of EFR-DWBA calculations. The dashed lines are the HF predictions, arbitrarily normalized. θ_2 is the α-particle angle defined in the recoil nucleus center-of-mass frame, but with respect to the beam direction.

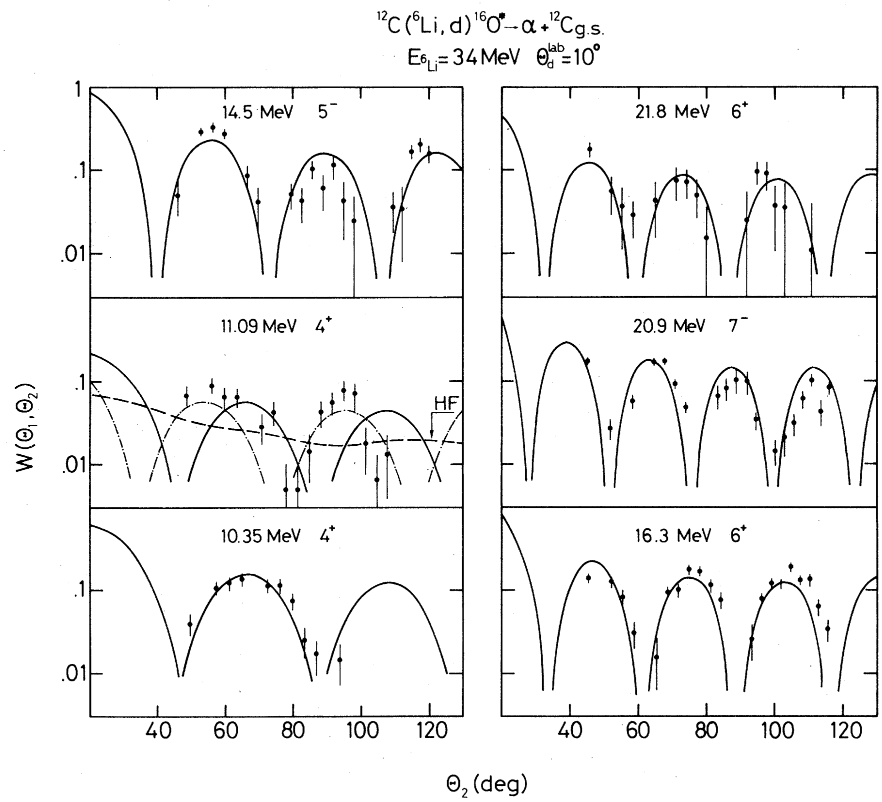

FIG. 5. d-α correlation functions for the $^{12}C(^6Li,d)^{16}O\to\alpha+^{12}C_{g.s.}$ reaction. Solid and dashed curves are as in Fig. 4. For the dot-dashed curve see text.

$P_1(\Omega_1)$ are the populations of the magnetic substates $m_{I'}=0$ and $m_{I'}=1$, respectively:

$$P_{m_{I'}}(\Omega_1)=\sum_{\substack{m_i m_I\\ m_{i'}}}|T^{m_i m_I}_{m_{i'} m_{I'}}(\Omega_1)|^2\Big/\sum_{\substack{m_i m_I\\ m_{i'} m_{I'}}}|T^{m_i m_I}_{m_{i'} m_{I'}}(\Omega_1)|^2 .$$

The values of $P_{m_{I'}}$ and δ deduced from ERF-DWBA and HF calculations are listed in Table III for the investigated ^{16}O levels. From Fig. 5 and Table III it appears that an overall agreement between DWBA calculations and experimental data is found for the considered cases, except for the α decay from the 11.09 MeV (4^+) level. For this transition in Fig. 5 the HF prediction is also reported as a dashed curve. The clear disagreement existing between both the theoretical predictions and data, indicates that the reaction mechanism involved in the population of this level cannot be explained in terms of one-step direct α transfer or of a statistical compound nucleus. However (see the dot-dashed curve in Fig. 5), a good fit to the data is obtained by shifting the DWBA curve 12°. A possible explanation for this "anomalous" shift, previously observed,[3] relies on the hypothesis that the primary reaction proceeds through a two-step direct mechanism. This would be also

TABLE III. Angular shifts and magnetic substates populations from EFR-DWBA and HF.

Level	J^π	δ_{exp}[a]	δ_{DWBA}	P_0(%)	P_1(%)	P_2(%)	δ_{HF}	P_0(%)	P_1(%)	P_2(%)
21.8	6^+	10°	11.36°	36.6	29.5	1.6	8.5°	30.8	21.9	9.7
20.9	7^-	11°	9.5°	41.1	27.2	2.2	7.4°	30.0	21.5	10.1
16.3	6^+	14°	13.6°	25.1	33.6	3.7	10.7°	26.3	21.1	10.8
14.5	5^-	16°	15.89°	20.1	37.1	2.9	13.9°	24.9	20.9	11.0
11.09	4^+	5°	17.47°	29.8	32.9	2.1	19.0°	23.1	20.4	11.6
10.35	4^+	19°	17.8°	28.4	33.1	2.6	19.3°	20.4	18.1	10.4

[a] An indetermination of ±0.5 for δ_{exp} is expected from the applied chi-square procedure.

TABLE IV. Decay properties of some ^{16}O levels.

E (MeV)	J^π	$\Gamma_{c.m.}$ (keV)[a]	P_l[b]	Γ_{α_0}/Γ	Γ_{α_0}/Γ[c]
21.8	6^+	55	0.966	0.67± 20%	
20.9	7^-	650 ± 75	0.727	1.16 ± 20%	
16.3	6^+	370 ± 40	0.455	1.07 ± 10%	0.90 ± 0.10
14.5	5^-	560 ± 75	0.583	1.03 ± 10%	0.75 ± 0.15
11.09	4^+	0.28 ± 0.05	0.127	0.31 ± 10%	
10.35	4^+	27 ± 4	0.033	0.86 ± 10%	0.90 ± 0.10

[a]Reference 25.
[b]Reference 26.
[c]Reference 8.

in agreement with the suggestions[4,14] that this level has an important core excited $[^{12}C_{2^+} \otimes {}^{20}Ne_{2^+}]$ structure.

B. Decay properties

From the expressions (3) and (2), the ratio Γ_{α_0}/Γ corresponding to the α decay to the ground state of the ^{12}C nucleus can be deduced. The results are summarized in Table IV. This ratio, which is consistent with the results obtained in Ref. 8, for the 10,35, 14.5, 16.3, and 20.9 MeV levels, results close to unity, confirming the α structure of these levels.

A more quantitative information about the structure of these ^{16}O levels is contained in the α-reduced widths which are related, in the approximations discussed in Refs. 15 and 16, to Γ_{α_0} by

$$\Gamma_{\alpha_0} \simeq 2P_l \gamma_{\alpha_0}{}^2 .$$

Figure 6 shows the Γ_{α_0} values, for each level, compared with the respective penetrabilities P_l. The existing proportionality in the case of the above levels indicates that the γ_{α_0} values are constant. A similar result was found in Ref. 13 in agreement with the classification of these levels into positive $K^\pi = 0^+$ and $K^\pi = 0^-$ α-rotational bands.

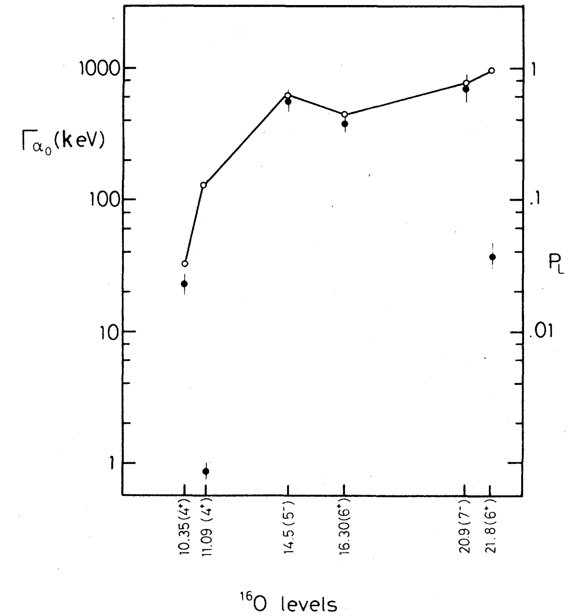

FIG. 6. Γ_{α_0} and P_l values for different ^{16}O α-decaying levels.

IV. CONCLUSIONS

The present work extends previous evidence on the sensitivity of the particle-particle angular correlation method to the reaction mechanism of the first-step process. In particular, we have shown that the EFR-DWBA reproduces the shift and the shape of the experimental data in the cases in which a direct α transfer is predominantly expected. The previously found[4] small contribution of the compound nucleus mechanism does not significantly change the position of maxima and minima of the correlation curves. When a more complicated reaction mechanism contributes, as in the 11.09 MeV (4^+) case, the correlation data are a more sensitive tool than the simple angular distribution.[4-6] Finally an additional support to the α-structure of some ^{16}O levels is derived from the extracted ratios Γ_{α_0}/Γ and α-reduced widths γ_{α_0}.

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