Interference effects between ^{17}O states populated in the ^{13}C(^{6}Li,d)^{17}O* $\rightarrow \alpha + ^{13}$C reaction

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An analysis of the ^{13}C(^{6}Li,dα)^{13}C reaction in the collinear ($\theta_d = 0°$) and noncollinear ($\theta_d = 10°,8°$) geometry is made for two peaks observed in the deuteron energy spectrum and corresponding to excitation energies of 16.1 and 13.6 MeV in the ^{17}O nucleus. It is shown that the reaction proceeds via a direct alpha-transfer process which populates doublets of interfering ^{17}O levels. Spins, weights, and parities of these levels are obtained by means of a least square procedure.

I. INTRODUCTION

In the past few years evidence has been given that the (^{6}Li,d) reaction induced on light nuclei selectively excites alpha-cluster states of the residual system.[1,2] If these states are unbound, a powerful method for the direct determination of their nuclear properties (spin, parity, and decay widths) is based on the measurement of the angular correlation between the deuterons emitted in the primary (^{6}Li,d) process and the alpha particles associated with the disintegration process.[3,4]

This method has been successfully applied to "zero spin" target nuclei.[3,5] In this case the experimental d-α angular correlation data are well reproduced by squared Legendre polynomials of order $L = I$ (I being the spin of the excited level), as expected,[3] if no spin-flip is assumed in the primary (^{6}Li,d) process and deuterons are emitted at $\theta_d = 0°$ (collinear geometry). Moreover, experimental observations and theoretical calculations done in the distorted wave Born approximation (DWBA) framework showed that, detecting the deuterons at a small angle (noncollinear geometry), the effect in the correlation curve was essentially an angular shift δ.[5]

In order to get information about the ^{17}O states lying at high excitation energy, d-α angular correlations for the reaction ^{13}C(^{6}Li,dα)^{13}C$_{g.s.}$, involving a "nonzero" spin target nucleus, have been measured by several groups.[6–8] In Ref. 6 the experimental data obtained detecting deuterons at $\theta_d = 8°$ were reproduced by shifted $|P_L[\cos(\theta-\delta)]|^2$ functions, i.e., as in the case of a zero spin target nucleus, even if no rigorous theoretical justification was given. The results of these fits were interpreted in light of the weak-coupling model, and well defined spin and parity values were assigned to some ^{17}O levels. However, as pointed out in Ref. 7, the marked periodical oscillations found in the experimental data cannot be reproduced assuming the population of a single intermediate ^{17}O nucleus level with defined spin and parity. Note that, as a possible explanation of this experimental behavior, the presence of a nonsequential mechanism has been suggested.[7,8]

On the other hand, the study of some ^{17}O α-cluster states lying at excitation energies below 13 MeV has been performed via the ^{13}C(α,n) and ^{13}C(α,α') reactions.[9] In particular, the experimental neutron angular distributions have been reproduced assuming interference between two closely spaced and overlapped ^{17}O states. The existence of a doublet centered at 13.6 MeV in the ^{17}O nucleus has been not excluded also by Clark *et al.*,[10] which compared the deuteron angular distributions from the reactions ^{12,13}C(^{6}Li,d)^{16,17}O* at 35.5 MeV incident energy.

On the basis of these observations it seemed to us worthwhile to test the hypothesis that some ^{17}O levels populated via a direct α transfer in the ^{13}C(^{6}Li,dα) reaction are overlapped and interfere.

This paper deals with the analysis of two transitions involving the peaks observed in the deuteron energy spectrum, lying at 16.1 MeV and 13.6 MeV of ^{17}O excitation energies, for which the d-α angular correlations have been measured both in the noncollinear[6,7] ($\theta_d = 8°$ and 10°) and, more recently, in the collinear geometry.[8]

In order to analyze these data, we extended the angular correlation formalism of Ref. 3, to take into account interference between two overlapping levels, each of given spin and parity.

A review of the experimental arrangements and results will be described in Sec. II while the theoretical scheme will be given in Sec. III. Sections IV and V will be devoted to the analysis of the experimental results and to the conclusions, respectively.

II. EXPERIMENTAL ARRANGEMENTS AND RESULTS

The $\theta_d = 10°$ and the $\theta_d = 0°$ experiments[7,8] were performed using isotopically enriched (97%) ^{13}C targets 150 μg/cm^2 thick, and the 34 MeV ^{6}Li^{3+} beam of the Tandem Van de Graaff laboratory at the Centre d'Etudes Nucléaires Saclay.

In the first experiment standard *DE-E* solid state telescopes were used to detect the deuterons and the coincident alpha particles. In the second experiment, deute-

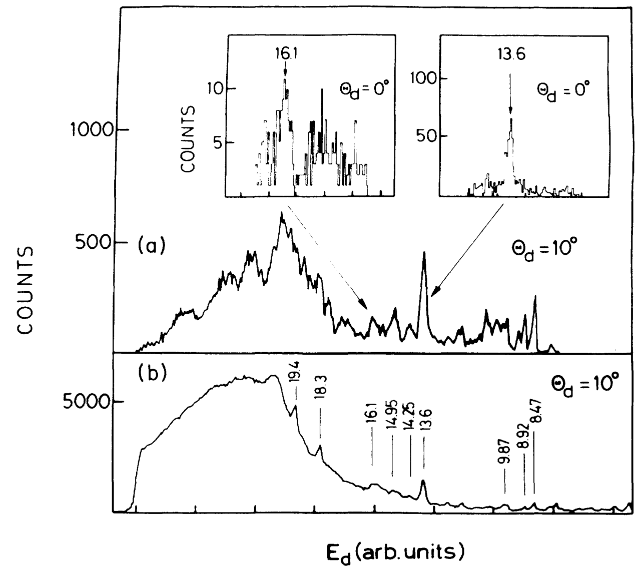

FIG. 1. Energy spectra from the $^{13}C + ^{6}Li$ reaction at $E(^{6}Li) = 34$ MeV. (a) Coincidence d-α spectra detected at $\theta_d = 10°$ and $\theta_d = 0°$ (insets). The 10° data are integrated on the whole measured angular range; the 0° data are integrated on the angles measured in a single run. (b) Single deuteron spectrum detected at $\theta_d = 10°$.

rons were detected at 0° ($\Delta\theta = \pm 1.7°$; $\Delta\phi = \pm 2.0°$) with the Saclay quadrupole-dipole-dipole-dipole (QDDD) magnetic spectrometer. Energy loss and position were measured along the focal plane with a resistive wire proportional gas counter, while residual energy and time information were provided by a plastic scintillator. The coincident alpha particles were detected by means of solid state detectors.

In both experiments the deuteron energy resolution (FWHM) was about 100 keV. In the $\theta_d = 10°$ experiment, the events due to ^{12}C impurity were subtracted on the basis of kinematics, whereas complementary measurements with natural carbon targets were done in the $\theta_d = 0°$ case.

The single and alpha-coincident deuteron energy spectra for the $^{13}C(^{6}Li, d\alpha)^{13}C$ reaction, observed at $\theta_d = 10°$, are shown in Fig. 1. In this figure the two α-coincident deuteron energy spectra measured at $\theta_d = 0°$ are shown in the insets. Note that random coincidences have been subtracted and that the continuous background, usually attributed to the ^{6}Li breakup, is small in the analyzed region.

The $\theta_d = 8°$ experiment was performed by Artemov et al.[6] at the cyclotron laboratory of the Kurchatov Institute using ^{6}Li beams of 26 and 29 MeV for the 16.1 and 13.6 MeV peaks, respectively. Deuterons were detected by a solid state telescope; α particles by means of single solid state detectors. The ^{12}C subtraction was performed on the basis of kinematics.

The experimental angular correlations for the three measured deuteron angles are shown in Fig. 2. All the data, i.e., in the collinear as well as in the noncollinear geometry, have marked periodical oscillations and show

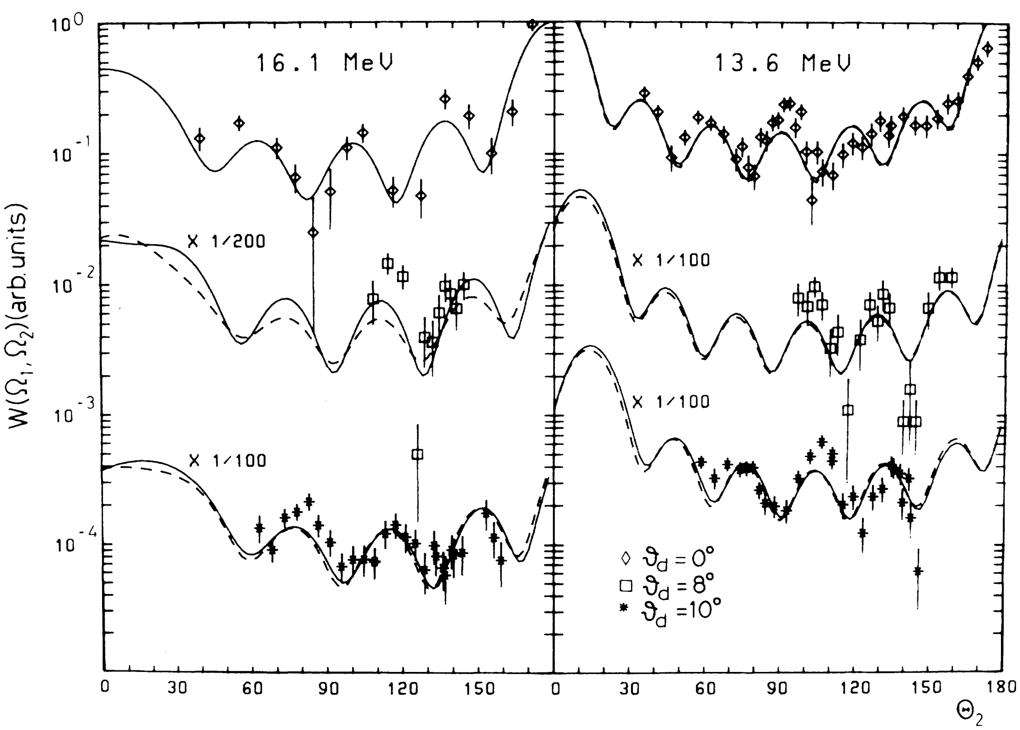

FIG. 2. Deuteron-alpha angular correlations for the transitions analyzed in the present work. For the 16.1 MeV resonance the solid line corresponds to $I'^{\pi} = \frac{7}{2}^-, \frac{11}{2}^+$; the dashed line to $I'^{\pi} = \frac{7}{2}^+, \frac{11}{2}^-$. At 0° the curves for the two cases coincide. For the 13.6 MeV resonance the solid line corresponds to $I'^{\pi} = \frac{11}{2}^+, \frac{13}{2}^+$; the dashed line to $I'^{\pi} = \frac{11}{2}^-, \frac{13}{2}^-$. θ_2 is the α-particle angle defined in the recoil nucleus center-of-mass frame, with respect to the beam direction. To report the 8° data in our reference frame they were shifted off the ^{17}O recoil angle. The azimuthal angles of deuterons and α particles are, respectively, $\phi_d = 0°$ and $\phi_\alpha = 180°$.

an angular shift which depends on the deuteron detection angle. The solid and dashed lines in Fig. 2 represent the calculations discussed in the following sections.

III. THEORETICAL SCHEME

In this section we review the particle-particle angular correlation formalism[2,3] and extend it in order to include interference due to the overlap of intermediate nucleus states.

Assuming that the reaction $X(^6\text{Li},\text{d})\text{Y}^* \to \alpha + X_{\text{g.s.}}$ proceeds via a sequential mechanism, the transition amplitude T of the whole process can be factorized as

$$T = T_1 T_2 \; , \tag{1}$$

where T_1 describes the primary process populating a well defined state of the Y* nucleus and T_2 its α decay.

The general expression of the angular correlation function $W(\Omega_1,\Omega_2)$ for this reaction is

$$W(\Omega_1,\Omega_2) = N \sum_{\substack{m_i m_I \\ m_{i'} m_{i''} m_{I''}}} \Big| \sum_{m_{I'}} T_{1_{m_{i'} m_{I'}}}^{m_i m_I}(\Omega_1) T_{2_{m_{i''} m_{I''}}}^{m_{I'}}(\Omega_2) \Big|^2 \; , \tag{2}$$

where Ω_1 and Ω_2 are the deuteron and α particle emission angles. I and m_I, i and m_i, i' and $m_{i'}$, i'' and $m_{i''}$, and I'' and $m_{I''}$ are the spins and their z projections of the X, ^{6}Li, d, α, and $X_{\text{g.s.}}$ nuclei, respectively. The constant N satisfy the normalization relationship

$$\int_{4\pi} W(\Omega_1,\Omega_2) d\Omega_2 = 1 \; . \tag{3}$$

If the Y* nucleus is populated via an α-transfer process, with no deuteron spin-flip, i.e., the deuteron is a spectator, T_1 can be expressed in the transferred angular momentum basis:

$$T_{1_{m_{I'}}}^{m_I}(\Omega_1) = \sum_{\substack{L l' \\ m_L m_{l'}}} \gamma_1 \gamma_2^{I'} \langle I I' m_I - m_{I'} \,|\, L - m_L \rangle \times \delta_{m_L m_l} \beta_{LL0}^{l' m_{l'}} P_{l'}^{m_{l'}}(\theta_1) \; , \tag{4}$$

where l is the orbital angular momentum in the exit channel, L is the transferred orbital angular momentum, and γ_1 and $\gamma_2^{I'}$ are the α-spectroscopic amplitudes in the ^{6}Li and Y* nuclei, respectively. The quantities $\beta_{LL0}^{l' m_{l'}}$ can be calculated by using a suitable DWBA code, e.g., SATURN-MARS.[11]

Taking into account that $i''=0$, T_2 can be written[3] as

$$T_{2_{0 m_{I''}}}^{m_{I'}}(\Omega_2) = \sum_{l'' m_{l''}} \langle l'' I'' m_{l''} m_{I''} \,|\, I'_{m_{I'}} \rangle \times S_{\alpha'' I'' l''}^{I'} Y_{l''}^{m_{l''}}(\Omega_2) \; , \tag{5}$$

where $S_{\alpha'' I'' l''}^{I'}$ are the decay matrix elements.

If interfering states are populated in the Y* nucleus, Eq. (2) must be modified by inserting a sum over I' inside the squared modulus.

When using zero or $\frac{1}{2}$ spin targets within our approximations, the parity conservation rule allows only one value for the angular momenta L and l'' for each spin I' and parity π of the Y* nucleus. Therefore, the angular correlation function can be written as

$$W(\Omega_1,\Omega_2) = N \sum_{m_I m_{I''}} \Big| \sum_{I' m_{I'}} A_{I'} \sum_{l' m_{l'}} \langle I I' m_I - m_{I'} \,|\, L - m_L \rangle \beta_{LL0}^{l' m_{l'}} P_{l'}^{m_{l'}}(\theta_1) \delta_{m_L m_{l'}} \langle l'' I'' m_{l''} m_{I''} \,|\, I' m_{I'} \rangle Y_{l''}^{m_{l''}}(\Omega_2) \Big|^2 \; , \tag{6}$$

where the $A_{I'}$ complex coefficients

$$A_{I'} = \gamma_1 \gamma_2^{I'} S_{\alpha'' I'' l''}^{I'} \; , \tag{7}$$

can be obtained by means of a least square fitting procedure of the data.

IV. ANALYSIS OF THE DATA

The aim of the present analysis is to get a coherent overall description of the data using expression (6) for two interfering levels.

For each peak and a given deuteron angle, we start searching for spin values and $A_{I'}$ coefficients which give the best fit of the data. Using these parameters, we compare the theoretical predictions with the data taken at the other deuteron angles within a scale factor. When changing the set of starting data, satisfactory fits are obtained and a very good stability is found upon the spin of the interfering levels. The summary of the results is given in Table I. As an example of the sensitivity of the method, the $\theta_d = 10°$ data are compared to different sets

TABLE I. Results of the fit procedure for the transitions analyzed in the present work.

$E(^{17}\text{O}^*)$	$I_1'^{\pi}$	$I_2'^{\pi}$	$\frac{\lvert A_1\rvert^2}{\lvert A_1\rvert^2+\lvert A_2\rvert^2}$	$\frac{\lvert A_2\rvert^2}{\lvert A_1\rvert^2+\lvert A_2\rvert^2}$	$\Delta\phi$
16.1	$\frac{7}{2}^-$	$\frac{11}{2}^+$	0.04	0.98	56
	$\frac{7}{2}^+$	$\frac{11}{2}^-$	0.35	0.65	218
13.6	$\frac{11}{2}^-$	$\frac{13}{2}^-$	0.58	0.42	179
	$\frac{11}{2}^+$	$\frac{13}{2}^+$	0.97	0.03	56

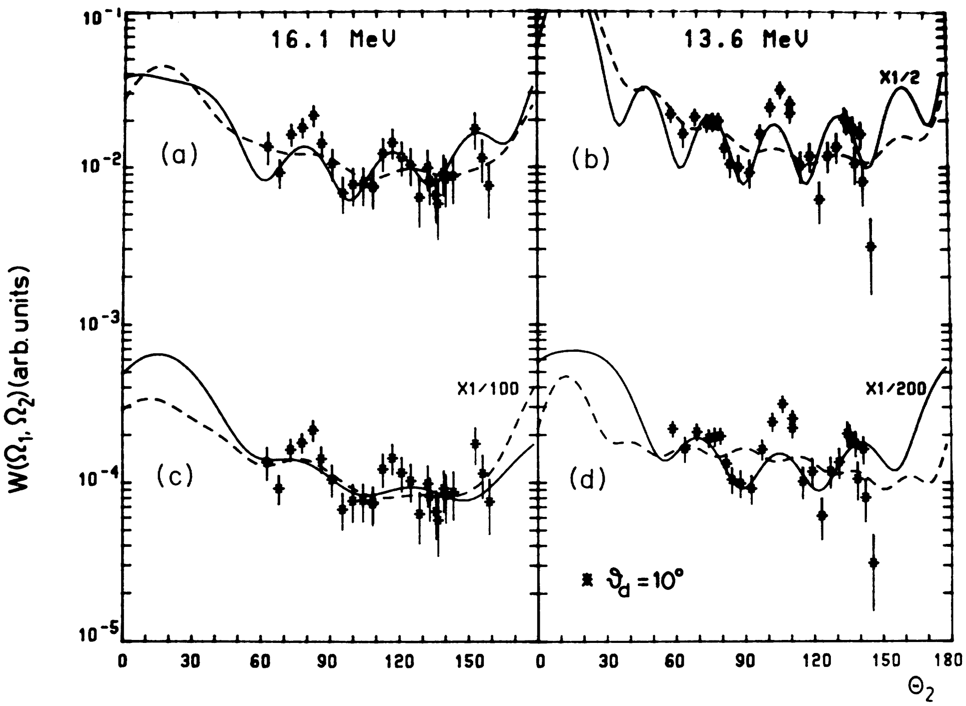

FIG. 3. Deuteron-alpha angular correlations at $\theta_d = 10°$ compared to calculations based on different spin and parity couples. The solid and dashed lines represent in (a) the couples $[\frac{7}{2}^-, \frac{11}{2}^+]$ and $[\frac{7}{2}^-, \frac{11}{2}^-]$, in (b) $[\frac{11}{2}^+, \frac{13}{2}^+]$ and $[\frac{11}{2}^+, \frac{13}{2}^-]$, in (c) $[\frac{7}{2}^-, \frac{9}{2}^+]$ and $[\frac{7}{2}^-, \frac{13}{2}^+]$, and in (d) $[\frac{11}{2}^+, \frac{9}{2}^+]$ and $[\frac{11}{2}^+, \frac{15}{2}^+]$.

of spins and parities of the interfering levels in Fig. 3, where the curves show the effect of changing the parity [Figs. 3(a) and 3(b)] and the spin [Figs. 3(c) and 3(d)] of one level. In Table II we show the DWBA parameters used in the T_1 matrix elements calculation.

A. The 16.1 MeV peak

We assume that the broad 16.1 MeV peak corresponds to the one observed by Artemov *et al.*[6] at 15.95 MeV. As mentioned above, these authors compared the d-α angular correlation for the ^{13}C(^{6}Li,dα)^{13}C reaction involving this peak, with the $|P_5[\cos(\theta-\delta)]|^2$, assigned the $L=5$ value to the $\alpha+{}^{13}$C relative orbital angular momentum, and, on the basis of weak-coupling arguments, suggested $I'=\frac{9}{2}^+$ for this level. Ajzenberg-Selove[12] reported $\frac{9}{2}^+$ and $\frac{11}{2}^+$ as possible spins and parities for this level.

The best couple of spins resulting from our analysis is $\frac{7}{2}$ and $\frac{11}{2}$. Moreover, at $\theta_d=0°$, the best fit is obtained in the hypothesis that the two levels have different parities. Note that at $\theta_d=0°$, the same curve can be obtained either using the spins and parities couples $(\frac{7}{2}^-, \frac{11}{2}^+)$ or the $(\frac{7}{2}^+, \frac{11}{2}^-)$, but with different $A_{I'}$ values (see Table I). The corresponding curves, shown in Fig. 2 together with those for $\theta_d=8°$ and 10°, nicely reproduce the experimental data. However, up to $\theta_d=10°$, there is not enough difference between the curves calculated for the two sets of parities to allow for parities assignment, as can be inferred from Fig. 4.

B. The 13.6 MeV peak

For the 13.6 MeV ^{17}O peak, Artemov *et al.*[6] gave $L=6$ and suggested $I'^{\pi}=\frac{13}{2}^-$. The $L=6$ value was suggested also by Clark *et al.*[10] from the comparison of the

TABLE II. DWBA parameters used in the calculations of the correlation functions (see Refs. 3 and 5).

Channel	V^a (MeV)	r_v (fm)	a_v (fm)	W^b (MeV)	r_w (fm)	a_w (fm)	r_c (fm)
^{6}Li + ^{13}C	250	1.354^c	0.650	30.0	1.354^c	0.650	2.0^c
d + ^{17}O	92.9	1.044^c	0.814	10.0	1.395^c	0.709	1.3^c
^{13}C + α	d	1.250^e	0.650				1.25
d + α	d	1.545^e	0.650				1.545^e

[a]Form factor: Woods-Saxon.
[b]Form factor: Woods-Saxon derivative.
[c] $R=rA^{1/3}$.
[d]Varied to reproduce separation energies.
[e] $R=r(A^{1/3}+a^{1/3})$.

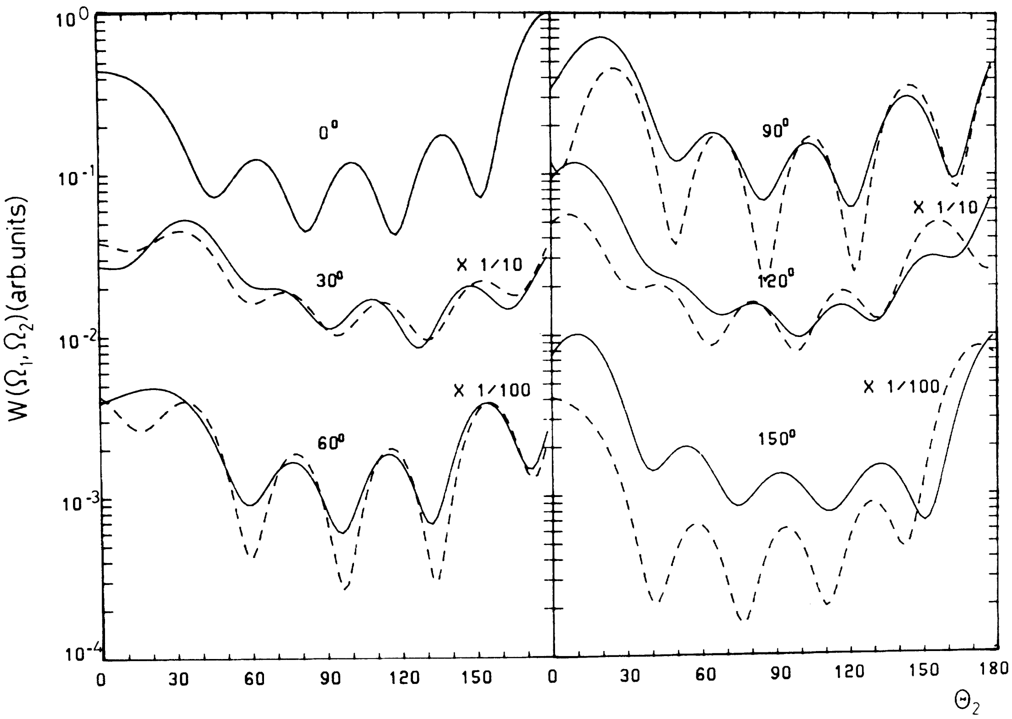

FIG. 4. Theoretical behavior of the angular correlation function calculated for $I'^{\pi}=\frac{7}{2}^-,\frac{11}{2}^+$ (solid line) and $\frac{7}{2}^+,\frac{11}{2}^-$ (dashed line), at different deuteron emission angles. The weights used for these calculations are those obtained in the fit of the 16.1 MeV resonance.

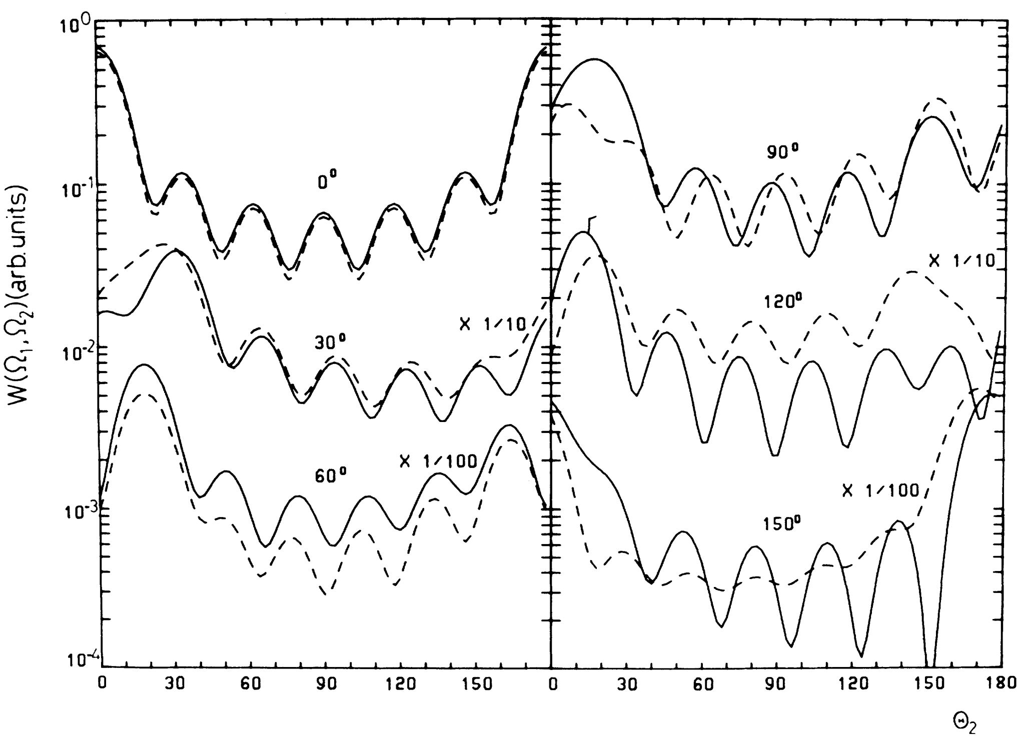

FIG. 5. Same as Fig. 4 for $I'^{\pi}=\frac{11}{2}^+,\frac{13}{2}^+$ (solid line) and $I'^{\pi}=\frac{11}{2}^-,\frac{13}{2}^-$ (dashed line). The weights used are those obtained in the fit of the 13.6 MeV resonance.

angular distributions of deuterons emitted in the $^{13}C(^{6}Li,d)^{17}O^{*}$ and $^{12}C(^{6}Li,d)^{16}O^{*}$ reactions at $E(^{6}Li)=35.5$ MeV involving the 13.6 MeV ^{17}O and the 16.3 MeV $6^{+16}O$ states, respectively. In particular, they suggest that this peak contains one or both members of the $\frac{11}{2}^-$, $\frac{13}{2}^-$ $(L=6)^{17}O$ doublet.

Applying our method, we can exclude that this peak corresponds to a single ^{17}O state and we reproduce the $\theta_d=10°$ angular correlation with $(\frac{11}{2}^+,\frac{13}{2}^+)$ as well as with $(\frac{11}{2}^-,\frac{13}{2}^-)$, getting rather similar χ^2 values in both cases. The theoretical curves fit the $\theta_d=8°$ data very well and agree with the $\theta_d=0°$ data only at forward angles. Kinematical calculations ruled out the hypothesis that the $\theta_d=0°$ data behavior at backward angles is due to the population of ^{15}N excited states in the $^{13}C(^{6}Li,\alpha)^{15}N^{*}\rightarrow d+{}^{13}C$ reaction.

In conclusion, the results of the present analysis agree with the suggestions of Ref. 10. In particular, if the two overlapped levels have the same $L=6$ value, i.e., $I'^{\pi}=\frac{11}{2}^-$, and $\frac{13}{2}^-$, one should infer that the spin-orbit interaction between the relative orbital angular momentum of the $\alpha+{}^{13}C$ system and the heavy target ^{13}C spin is vanishingly small. This result would be consistent with the analysis of the ^{19}F α-cluster states,[13] but is in contrast with the observed spin-orbit splitting of ^{17}O α-cluster states at low excitation energy.[6,14]

V. SUMMARY

In this paper the hypothesis that the $^{13}C(^{6}Li,d)^{17}O^{*}\rightarrow\alpha+{}^{13}C$ reaction proceeds via a direct α-transfer mechanism populating two interfering ^{17}O levels has been assumed, and a coherent overall description of the available d-α angular correlation data has been obtained. In particular, we have compared the data taken both in the collinear and noncollinear geometry, getting evidence that the peak lying at 13.6 MeV excitation energy in the ^{17}O nucleus is due to the population of two interfering levels having the same parity and spin $\frac{11}{2}$ and $\frac{13}{2}$. In a similar way, the 16.1 MeV peak seems to be due to the population of levels with spin $\frac{7}{2}$ and $\frac{11}{2}$ and different parities, in contrast with previous spin suggestions.

The present analysis indicates that the measurements of angular correlations at small deuteron angles allow for spin assignment of the involved levels, while, as can be inferred from Figs. 4 and 5, information on the parities would be reached with data taken at large deuteron angles.

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