Doorway states and cross-section fluctuations in the $^{12}C(^{16}O,\alpha)$ reaction

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It is suggested that the deviations from pure Hauser-Feshbach predictions found in the already published analysis of $^{12}C(^{16}O,\alpha)$ data might be due to neglect of important multistep compound contributions. An appropriate multiclass fluctuation analysis clearly indicates the presence of two correlation widths, which can be associated with the population of two classes of overlapping states: one made up of doorway states, revealed by the largest of the observed coherence widths, and another made up of compound nucleus states connected with the fine structure of the fluctuating excitation functions. This interpretation was reinforced by new measurements on both excitation functions and complete α spectra. In addition, comparison of these data with calculations based on the quantum statistical multistep compound theory confirmed the importance of precompound effects and shed light on the nature of such doorway states which were found to be made up of 5p-1h configurations. These results support the hypothesis of Voit *et al.* that the first interaction between such light heavy-ion systems is dominated by the formation of α-particle doorway states.

I. INTRODUCTION

Recently, the usefulness of multiclass fluctuation analysis of excitation functions to explain the reaction mechanism was clearly demonstrated in the case of light-ion induced reactions.[1]

Subsequently, it was suggested that a similar type of analysis could be applied in the case of light heavy-ion data, including both reaction channels[2] and elastic scattering.[3] Such analysis clearly pointed out the overall importance of precompound effects of a multistep compound nature at moderate (just above-barrier) energies.

In the case of light-ion reactions the largest of the two correlation widths extracted from the fluctuating excitation functions could be attributed simply to the overlapping of a few exciton states, formed in the composite system at the time of the initial interaction. On the other hand, the interpretation of the same effect in the case of heavy-ion reactions is not so obvious. Perhaps the case of elastic scattering is the simplest one; here evidence was accumulated pointing to the formation of a class of overlapping molecular states that act as a doorway to compound nucleus (CN) formation.[3]

In the case of heavy-ion reactions, however, any classification of nuclear states in terms of a given number of excitons (p-h) is rather questionable. Moreover, due to the many possibilities open to the incoming ion at the time of the initial interaction (partial or complete fragmentation), to the strong energy dependence of such an interaction,[4] and to the degree of rearrangement of the composite system in connection with a particular outgoing channel, figuring out the details of the reaction mechanisms could be quite an intricate and, of course, interesting problem.

With this in mind, the study of a classical heavy-ion reaction, $^{12}C(^{16}O,\alpha)$, was undertaken at just-above-barrier energies.

It is the aim of this paper to show that an appropriate statistical analysis of the fluctuating excitation functions based on new methods,[5-7] and the interpretation of the other experimental aspects in terms of recent quantistic precompound theories,[8] might help to overcome some discrepancies and difficulties encountered in applying the traditional compound nucleus theories, as well as to clarify some of the above points.

This paper can be outlined as follows. Some of the already published results of the $^{12}C(^{16}O,\alpha)$ reaction are reanalyzed in Sec. II in the framework of the spectral density method and the multiclass correlation functions. In Sec. III new experimental results of excitation functions and α spectra are presented and analyzed with the same methods in Sec. IV. In Sec. V some comparisons with theoretical predictions of the statistical multistep compound theory are made. Finally, Sec. VI presents some conclusions.

II. REANALYSIS OF PREVIOUS ANALYSIS

Regarding further exploration of a reaction as widely studied as $^{12}C(^{16}O,\alpha)$, one certainly has the advantage of a large amount of experimental data and related analysis; on the other hand, the disadvantage is that it might be very difficult to destroy or correct some opinions about which there seems to be general agreement, such as the dominating compound-nucleus nature of such a reaction in the 25—45 MeV range. In our reanalysis of already published results, we isolated cases in which such an interpretation seemed definitely doubtful.

Halbert *et al.*[9] made very careful and complete measurements on excitation functions of the low-lying states populated by the $^{12}C(^{16}O,\alpha)$ reaction at $E=20$—43 MeV.

A statistical analysis of the fluctuating excitation functions based on the Ericson one-class autocorrelation func-

tion gave an average coherence width Γ of ~ 110 keV, which was stated to be consistent with a compound nucleus description of the reaction. However, if we look carefully at the coherence widths extracted for the different residual nucleus levels and emission angles before the average was figured, we find values for Γ ranging from 83 to 414 keV. In a subsequent paper on angular distributions,[10] Γ values ranging from 50 to 250 keV were extracted for different angles.

A similar situation also exists in the work of Gomez del Campo *et al.*,[11] where coherence widths from 60 to 280 keV were extracted for several levels excited up to 12.12 MeV. Again, an average coherence width was calculated from these values and its ~ 100 keV value was found to be consistent with compound nucleus predictions.

We would like to stress not only that taking an average of such widely varying values might not be significant, but also that it might lead to a loss of information on the reaction mechanism carried out by the different Γ values. As was clearly demonstrated in the case of light-ion reactions,[1] the widely varying Γ values could well be a sign of the various steps through which the system passes on its way towards the equilibrium (compound nucleus) state. This new point of view implies that use of the traditional one class Ericson autocorrelation function might be misleading, since in the case of several classes of simultaneously present overlapping states, it would make it possible to extract only a sort of weighted average of the various widths.[1,5,6]

In order to verify the above ansatz, we reanalyzed the fluctuations measured by Halbert *et al.*[9] by means of two recently developed methods: the spectral density method[5] and the multiclass generalized autocorrelation function.[6] Both methods are useful in the determination of the different coherence widths which can be present at the same time and they have already been widely applied and discussed.[1-3]

In the case of the generalized autocorrelation function, however, we used a particular formulation which was deduced more recently by McVoy and Tang[7] in the framework of the statistical multistep compound emission[8] (SMCE) cross section, but which had never been applied for practical analysis. This was done in order to be consistent with the theoretical interpretation of the results obtained using the SMCE theory, as will be discussed in Sec. V.

In its original formulation the generalized autocorrelation function was deduced on the basis of the nested doorway model[6] and in the absence of direct effect it reads

$$c(\epsilon)=\left|\sum_n \langle\sigma_n^{\mathrm{fl}}\rangle \frac{\Gamma_n}{\Gamma_n+i\epsilon}\right|^2, \tag{1}$$

where $\langle\sigma_n^{\mathrm{fl}}\rangle$ is the average value of the fluctuating cross section connected to the n stage, whose mean lifetime τ_n is related to the width Γ_n through the uncertainty relation.

The autocorrelation function obtained[7] within the multistep compound theory of Feshbach *et al.*[8] has the same multiclass structure as the above expression,

$$c_{ab}(\epsilon)=\left|\sum_n T_1 \prod_{k=1}^{n-1}\left[\frac{-\Gamma_{k,k+1}}{\Gamma_{kk}-i\epsilon}\right]\frac{D_n}{\Gamma_n-i\epsilon}\frac{T_b^n}{2\pi}\right|^2, \tag{2}$$

where, in the notation of the SMCE theory,

$$\Gamma_k=\Gamma_k^{\downarrow}+\Gamma_k^{\uparrow}$$

is the total width of stage k,

$$T_b^n=\frac{2\pi\Gamma_n^b}{D_n}$$

is the strength function for the formation of stage n, and

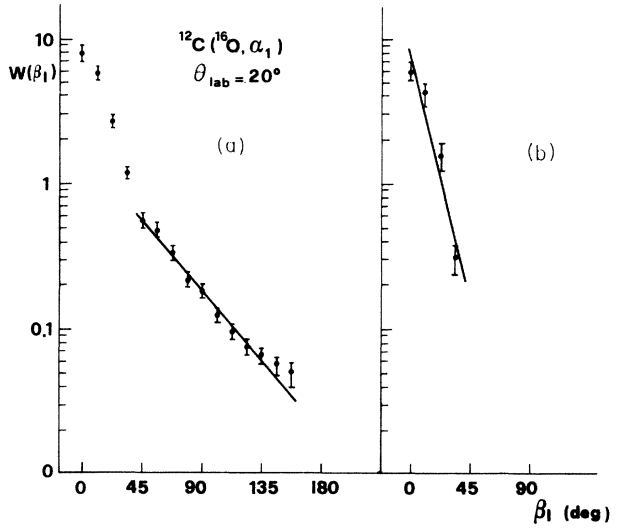

FIG. 1. Results of analysis with the spectral density method of $^{12}C(^{16}O,\alpha)$ at 20°. The straight lines are least squares fit of the experimental points and correspond to (a) $\Gamma_2=66$ keV, $\langle\sigma_2\rangle=15\%$ and (b) $\Gamma_1=217$ keV, $\langle\sigma_1\rangle=85\%$. The points in (b) have been obtained by subtracting the contribution of Γ_2 from the spectral density function shown in (a).

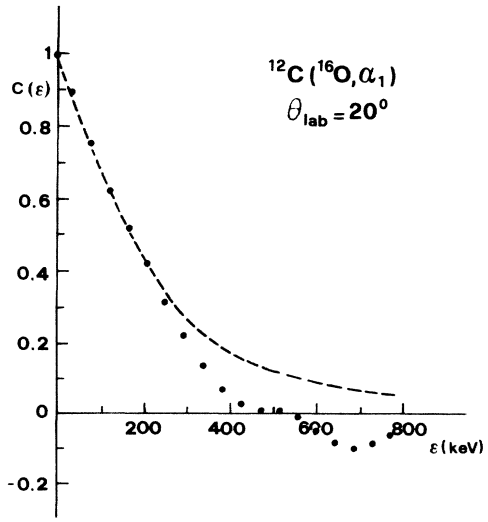

FIG. 2. Result of the analysis with the multiclass autocorrelation function of the same data as Fig. 1. Using $\Gamma_1=217$ keV and $\Gamma_2=66$ keV, the best fit was obtained with $\langle\sigma_1\rangle=90\%$, $\langle\sigma_2\rangle=10\%$.

TABLE I. Results of the statistical analysis of the data measured in Ref. 9 with $\Delta E=43$ keV. Columns 3 and 4 show the coherence widths in keV extracted with the spectral density method (SDM), columns 5 and 6 their relative cross sections, and columns 7 and 8 the relative cross sections extracted with the multiclass autocorrelation function (AF) by using the same Γ_2 and Γ_2 values as obtained with the spectral density method.

Angle (deg)	Group	Γ_2	Γ_1	$\langle\sigma_2\rangle^{SDM}$	$\langle\sigma_1\rangle^{SDM}$	$\langle\sigma_2\rangle^{AF}$	$\langle\sigma_1\rangle^{AF}$
0	α_0	62±10		1		1	
	α_1	50±6	246±70	0.1	0.9	0.2	0.8
	α_{2+3}	55±7	157±33	0.13	0.87	0.13	0.87
	α_5	83±13		1		1	
	α_6	63±8	223±56	0.07	0.93	0.07	0.93
20	α_0	45±6	158±43	0.16	0.84	0.11	0.89
	α_1	66±10	217±58	0.15	0.85	0.1	0.9
	α_{2+3}	60±8	403±136	0.11	0.89	0.11	0.89
	α_4	66±10	380±129	0.11	0.89	0.06	0.94
	α_{5+6}	66±10	183±41	0.19	0.81	0.1	0.9

$$-\frac{\Gamma_{k,k+1}}{\Gamma_{kk}}=\frac{\Gamma_k^{\downarrow}}{\Gamma_k}$$

is the depletion factor. With the hypothesis supported by analysis of both light-[1] and heavy-ion[2] reactions that only two steps are present or in any event are dominant, formula (2) easily reduces to

$$C_{ab}(\epsilon)=\left|\frac{2\pi\Gamma_1^i}{D_1}\left[\frac{\Gamma_b^{\uparrow}}{\Gamma_1-i\epsilon}+\frac{\Gamma_1^{\downarrow}+\Gamma_r^{\uparrow}}{(\Gamma_1-i\epsilon)(\Gamma_r-i\epsilon)}\right]\right|^2, \quad (3)$$

where $2\pi\Gamma_1^i/D_1$ is the strength function for forming the first step (the doorway or precompound stage) from the incident channel, Γ_1 and Γ_r are the average widths of the precompound first stage and of the compound r stage, and $\Gamma_b^{\uparrow}$ and $\Gamma_r^{\uparrow}$ are the escape widths to the continuum through channel b.

We want to point out that the quantity $\Gamma_b^{\uparrow}$ is related to the average cross section $\langle\sigma\rangle$ of Eq. (1) by the equation $\langle\sigma_1\rangle=\Gamma_b^{\uparrow}/\Gamma_1$ (a similar equation holds for $\Gamma_r^{\uparrow}$).

For transitions leading to the continuum part of the spectrum, where the statistical approximation is applicable, the SMCE enables the above quantities to be easily calculated in the framework of a given description of the excitation process (for details on calculations using a p-h description, see Refs. 1 and 12), while in the case of transitions to resolved states the $\Gamma_b^{\uparrow}$ quantities contain an unknown spectroscopic factor dependent on the structure of the particular channel b.

As already mentioned in the discussion of Eq. (1) in Ref. 1, this fact could lead to ambiguity in the extraction of Γ's by means of Eq. (3) since different combinations of Γ_1, Γ_r, $\Gamma_b^{\uparrow}$, and $\Gamma_r^{\uparrow}$ could, within certain limits, give equally acceptable fits to the experimental autocorrelation functions. We therefore first used the spectral density method, which allows an *a priori* determination of the above quantities.[5] The results were checked afterwards by using Eq. (3), in which the Γ_1 and Γ_2 values determined by means of the spectral density method were attributed to Γ_1 and Γ_2 of Eq. (3). In this way the reliability of the results was checked by comparing the relative cross sections obtained by the two independent analyses.

The analysis was done for the excitation functions measured by Halbert *et al.*[9] at 0° and 20°, where the largest anomalies were found (see Table II of Ref. 9).

The results are shown in Table I, and a typical example of analysis with both methods is shown in Figs. 1 and 2.

The most striking feature for several cases is the simultaneous presence of two widths, the smallest of which, Γ_2, with an average value of ~ 60 keV, is consistent with other measurements made on the same compound ^{28}Si nucleus at the same excitation energy.[1,13] On the other hand, the largest Γ value, Γ_1, is too large to be interpreted as being connected with the formation of the compound nucleus. Halbert *et al.* found the same discrepancy, although their analysis was not able to separate the different Γ values. They attributed this partly to the presence in the α_{2+3} and α_4 excitation functions at 20° of a clearly correlated structure at 31.8 MeV whose nonstatistical origin was explained by these authors.[9] In any event, we want to stress that the large width effect is also clearly present in other cases ($\alpha_1, \alpha_{2+3}, \alpha_6$ at 0°; $\alpha_0, \alpha_1, \alpha_{5+6}$ at 20°) where no correlated bump is seen. Moreover, the results found by using the spectral density method are confirmed by the generalized autocorrelation function analysis [Eq. (4)]. In fact, columns 7 and 8 of Table I show that, by using the same Γ widths extracted with the spectral density method, consistent $\langle\sigma\rangle$ values for the two classes are obtained.

There is therefore strong evidence to support the hypothesis that at least two classes of overlapping states are populated in ^{12}C(^{16}O,α) and that they show up in the fluctuating excitation functions of different levels with different relative weights due both to the different structure of the levels involved and to the different angular distributions of the statistical processes active in the reaction. In particular, emission from the first stage of the equilibration chain seems to be dominant at 20°.

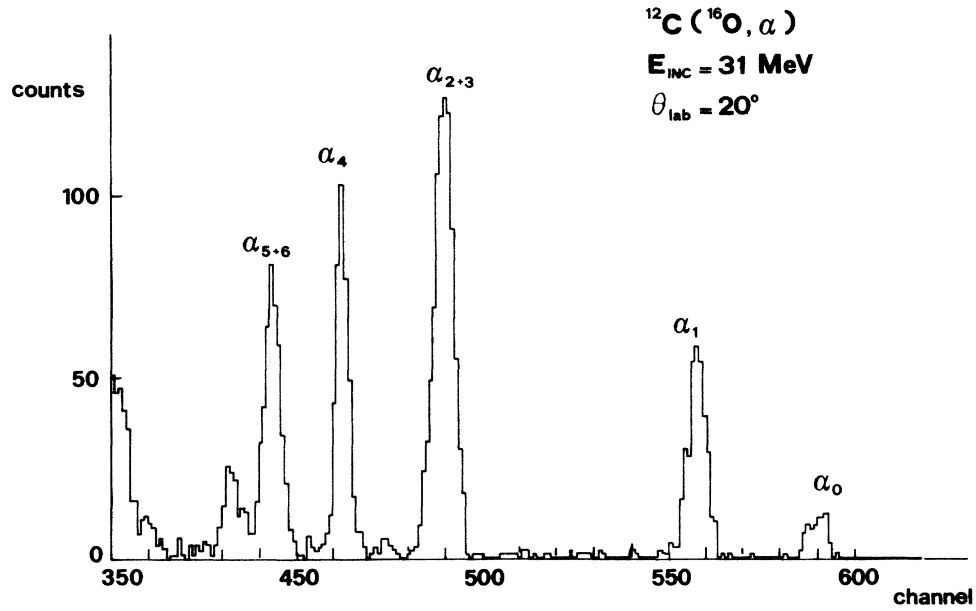

FIG. 3. A typical spectrum showing the region of interest at $E_{^{16}O} = 31$ MeV, $\theta_{lab} = 20°$.

III. DESCRIPTION OF NEW EXPERIMENTS ON THE $^{12}C(^{16}O,\alpha)$ REACTION

Motivated by the above results and with the aim of strengthening the findings outlined in the preceding section, we took some new measurements on the $^{12}C(^{16}O,\alpha)$ reaction. In particular, we measured (a) the excitation functions of low-lying levels at 20° and 133.5° (lab) from 24 to 43.2 MeV (lab) incident energy, and (b) the complete α spectrum at 40 MeV.

The excitation functions were measured at the two angles symmetric to 90° (28° and 152° in the center of mass) to check the hypothesis that the two extracted widths are connected with two quasiequilibrium and equilibrium stages, whose emission, according to any statistical description, should be symmetric around 90°. In fact, this is quantitatively predicted by the SMCE theory, as will be discussed in Sec. V. Of course, within this general symmetry, different structures and oscillations for the two stages are possible, in principle.[14] Finding the same Γ values at two symmetric angles would thus give important support to our interpretation since this would be a sign of equal relative weights [$\langle\sigma\rangle$ in Eq. (1) or $\Gamma_b^{\dagger}$ in Eq. (3)] for the two angles and therefore of angular distributions symmetric to 90° for the two stages.

The α spectrum was measured for comparison with the SMCE theory predictions, with the aim of better establishing the nature of the doorway states active in the reaction. The experiments were done at the Tandem Laboratory of the Laboratori Nazionali di Legnaro. The 4^+ or 5^+ ^{16}O beam was focused on a ^{12}C target, 20 $\mu g/cm^2$ thick. For the excitation function measurement, α particles were detected by two silicon detectors, placed at 20° and 133.5° (lab), with thicknesses of 1000 and 100 μm, respectively. The angular acceptance of the detectors was 2.3° and 3.8°, respectively. Mass discrimination between light-reaction products was easily achieved simply on the basis of the Q values and the energy loss of different particles in the detectors, while a Ni foil 7.5 μm thick was placed in front of the 20° detector to almost completely absorb the scattered ^{16}O and other heavy ions. Since the main purpose of this study is to investigate the large width effect, the fine structure having been thoroughly investigated by Halbert *et al.*,[9] we decided to use a relatively large energy step, 200 keV (lab) ($\sim$86 keV c.m.), which also helps limit the need for beam time. A typical spectrum giving the region of interest is shown in Fig. 3.

Complete α spectra were measured in a separate run by using a ΔE-E telescope at 20° lab. In this case, to optimize the resolution, the angular acceptance was limited to 0.5°. The detectors were a 25 μm Si one and a 5000 μm Si(Li) one, respectively. The thickness of the system was therefore enough to stop even the most energetic protons. Particle discrimination was achieved by constructing ΔE-$\Delta E + E$ bidimensional matrices.

IV. STATISTICAL ANALYSIS OF EXPERIMENTAL RESULTS

The excitation functions are shown in Figs. 4 (20°) and 5 (133.5°). The excitation functions at 20° are consistent with those measured by Halbert *et al.* and show clearly, in the case of α_{2+3} and α_4 channels, the nonstatistical bump at 31.8 MeV. Those at 133.5°, which had never been measured before, also exhibit a striking fluctuating character; however, no correlated bump is visible at 31.8 MeV.

The statistical analysis of the fluctuations was again done using the spectral density method. In the case of 20° excitation functions, to avoid the effect of the nonstatistical structure at 31.8 MeV which could give a nonphysical

enlargement of the extracted coherence widths, we decided to cut off the bump from the analysis. This was done by applying the spectral density method to two separate parts of the excitation functions, from the lowest energy value (24 MeV) to the beginning of the bump, and from the end of the bump to the highest energy value (43.2 MeV). Although the bump is clearly present only in the 20° excitation functions of the α_{2+3} and α_4 channels, for the sake of uniformity we decided to use the above criterion for all the excitation functions. The results, labeled Γ^{pre} and Γ^{post}, respectively, are shown in Table II. Three points should be stressed.

(i) The disappearance of the small width ~ 60 keV, which is a combined effect of both the relatively large energy step ΔE that was used (86 keV c.m.) and of its small weight (see the result of the analysis on the $\Delta E = 43$ keV data, Table I.

(ii) The disappearance of the very large Γ value, about 350–400 keV, previously extracted for α_{2+3} and α_4 at 20°, clearly due to the nonstatistical bump.

(iii) The consistency of Γ values extracted for the two symmetric angles and for the different α channels, giving an average value of ~ 200 keV.

The latter value is the same as the Γ value extracted from the $\Delta E = 43$ keV data (see Table I) and is clearly different from the "small" Γ value of ~ 60 keV, which, in turn, is

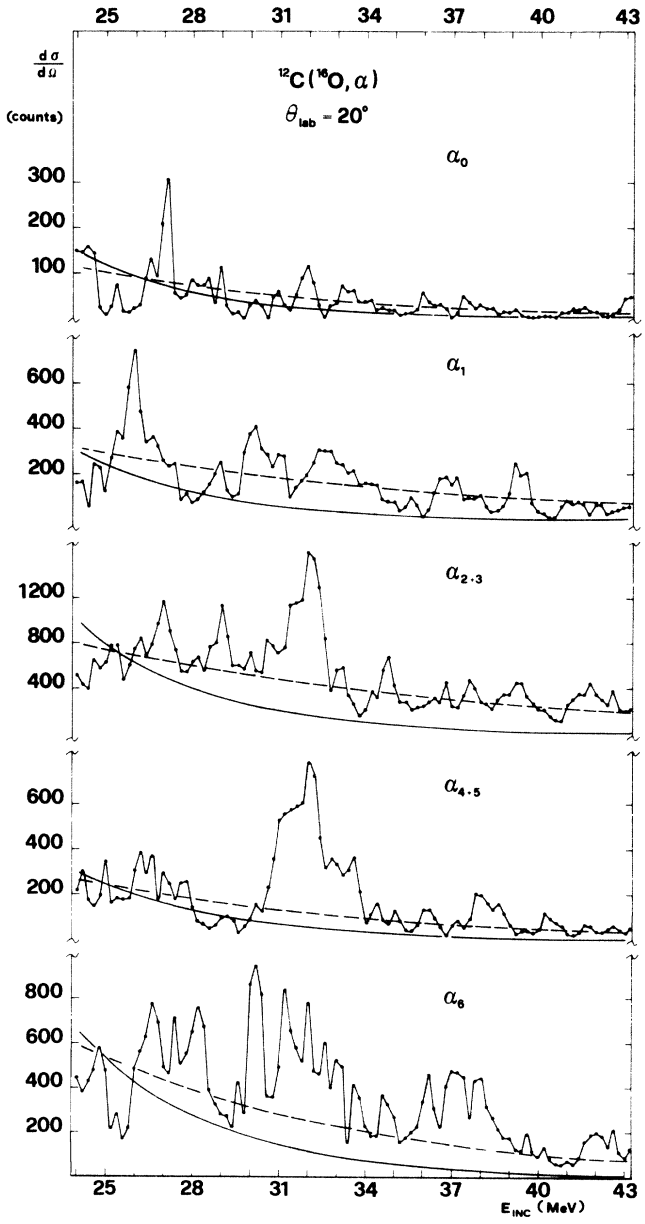

FIG. 4. Excitation functions at 20° for some low-lying levels in $^{12}C(^{16}O,\alpha)$. The curves are the result of SMCE calculations for the $n_0 = 6$ term (dashed line) and the r term (solid line).

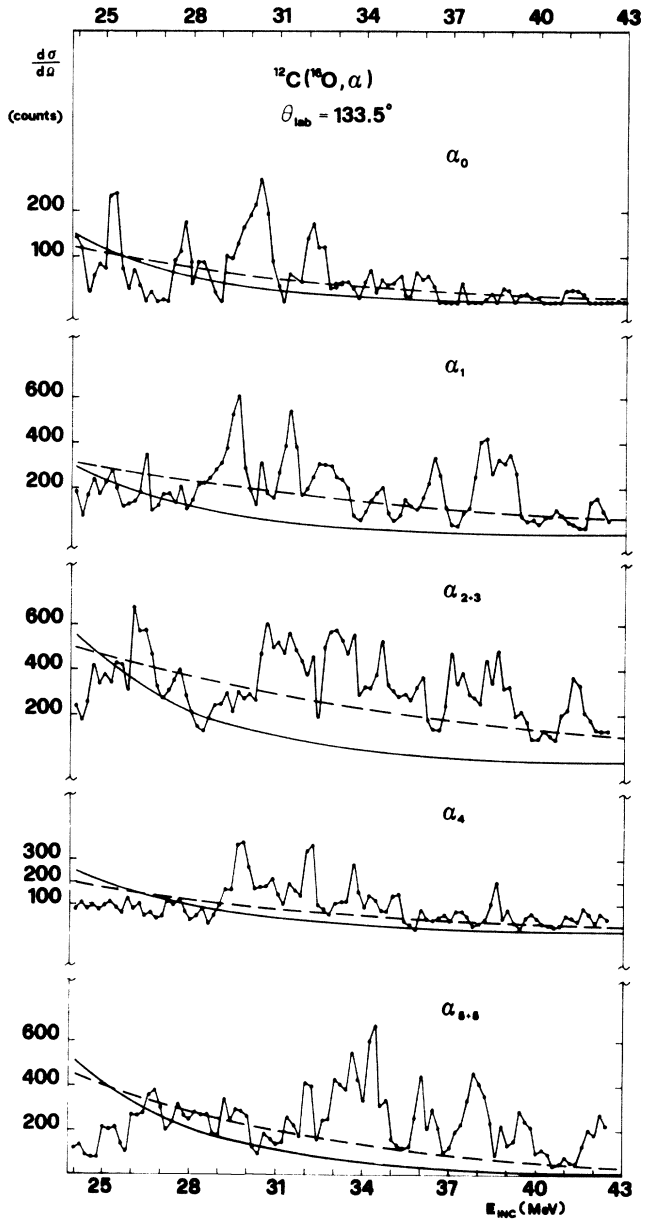

FIG. 5. Same as for Fig. 3, at 133.5°.

TABLE II. Results of analysis with the spectral density method of the $\Delta E=86$ keV data measured in this work, before (Γ^{pre}) and after (Γ^{post}) the nonstatistical structure at 31.8 MeV (see text). The Γ values are in keV.

Angle (deg)	Group	Γ^{pre}	Γ^{post}
20	α_0	184±12	201±14
	α_1	252±36	229±27
	α_{2+3}	198±17	214±33
	α_4	182±15	212±13
	α_{5+6}	165±14	258±34
133.5	α_0	155±14	167±8
	α_1	143±8	196±24
	α_{2+3}	170±13	178±25
	α_4	197±5	167±23
	α_{5+6}	244±18	196±31

consistent with compound nucleus (CN) predictions.[1,13]

We therefore believe that these results provide convincing arguments in support of a significant presence of precompound emission connected with the Γ_2 coherence energy. In this picture, the equilibration process of the intermediate system would proceed through two main stages corresponding to the excitation of two classes of states with rather different lifetimes.

V. THEORETICAL CALCULATIONS

It was shown in previous papers[1,12] that a correct reproduction of the experimental data on some light-ion reactions at moderate energies was given by the SMCE theory. This theory does, in fact, make it possible to calculate the emission of precompound particles from a chain of quasiequilibrium stages of increasing complexity and lifetime which ends with the equilibrium compound nucleus state, that acts as the last step in the chain (the "r stage"). The angular distribution of the particles emitted from each step should be symmetric around 90°. This feature present in the ^{12}C(^{16}O,α) data,[10] together with the presence of two classes of states with rather different lifetimes, supports the use of the SMCE theory in the interpretation of the experimental features in the ^{12}C(^{16}O,α) reaction.

A. The α spectrum

The α spectrum was calculated by means of the SMCE formula,

$$\frac{d\sigma}{dU}=\frac{\pi}{k^2}\sum_{m=1}^{r}\sum_{\nu=m-1}^{m+1}\frac{\langle\rho_{\gamma\nu}(U)\Gamma_m^{\gamma\nu}(U)\rangle}{\Gamma_m}\times\left[\prod_{k=1}^{m-1}\frac{\Gamma_k^{\downarrow}}{\Gamma_k}\right]\frac{2\pi\Gamma_1^i}{D_1}, \quad (4)$$

where m labels the stage and ν the exit mode, Γ_m is the total width of stage m, $\Gamma^{\downarrow}$ is the damping width while $\langle\rho_{\gamma\nu}(U)\Gamma_m^{\gamma\nu}(U)\rangle$ is the width for emission into the continuum, leaving the residual nucleus [with level density $\rho_{\gamma\nu}(U)$] at excitation energy U, γ labels all the quantum numbers necessary to completely specify the states, and Γ_1^i represents the width for the forming the first step from the initial channel.

From Eq. (4) it is evident that the shape of the spectrum, as is true of any preequilibrium cross section, depends strongly [through the $\rho_\nu(U)$ term] on the nature of the dominating configuration, which leads to particle emission and which is normally the one populated in the first step (which, for such light systems, is the only one).

Therefore, comparison of data could lead to discovery of the so-called number of initial degrees of freedom, n_0, and, consequently, to identification of the structure of the overlapping doorway states which give rise to the large correlation width Γ_1 previously extracted.

First of all, we should point out that n_0 is not expected to be too large. It is very unlikely, indeed, due to the relatively low incident energy ($\sim$1 MeV/nucleon in the c.m. system) and to the relatively high binding energy of ^{16}O and ^{12}C, that either of the two interacting nuclei would be completely fragmented. Indeed, the results of Ref. 4 indicating that n_0 is close or equal to the mass number of the incident ion have been obtained at much higher energy (10—20 MeV/nucleon). However, a partial fragmentation is certainly energetically possible.

Using the parameters from previous work[1,12] on reactions leading to the same ^{28}Si intermediate system, we therefore calculated the spectrum shape at 20° and 40 MeV with the SMCE theory. In using Eq. (4) we had to take into account the fact that the incident particle is a heavy ion. This would imply, in particular, a complete reformulation of the strength function $2\pi\Gamma_1^i/D_1$ in respect to the one which was worked out for nucleon-induced reactions in Ref. 8.

Due to the microscopic description adopted in Ref. 8 for the excitation process, the above calculation would be in this case a very involved one. We therefore preferred to resort to the relationship $2\pi\Gamma_l/D_l=T_l$, as we did in previous work on ^{3}He-induced reactions.[1,12] The use of the above relation is indeed well justified in the present case. Symmetric about 90° angular distributions clearly show that the loss of the incident flux due to direct-like processes is negligible.

The results for a few choices of n_0 corresponding to the most plausible configurations are shown in Fig. 6. The best reproduction of the spectrum shape is achieved with $n_0=6$ (5p-1h), which seems to indicate the break up of ^{16}O into four fragments with excitation of a p-h pair at the same time. To explain the nature of such excited fragments, only hypotheses based on qualitative arguments are possible at the present stage of the investigation.

Indeed, the well-known α particle structure of the two colliding nuclei, together with the fact that the final α channels are the most strongly populated among other light particles, as well as simple energetic considerations about the various possible fragmentations of ^{12}C and ^{16}O, all strongly suggest that we are dealing here with α particle excitations.

Another important result confirmed by SMCE calculations is that only two stages are present in the reaction: the precompound $n_0=6$ stage and the residual equilibri-

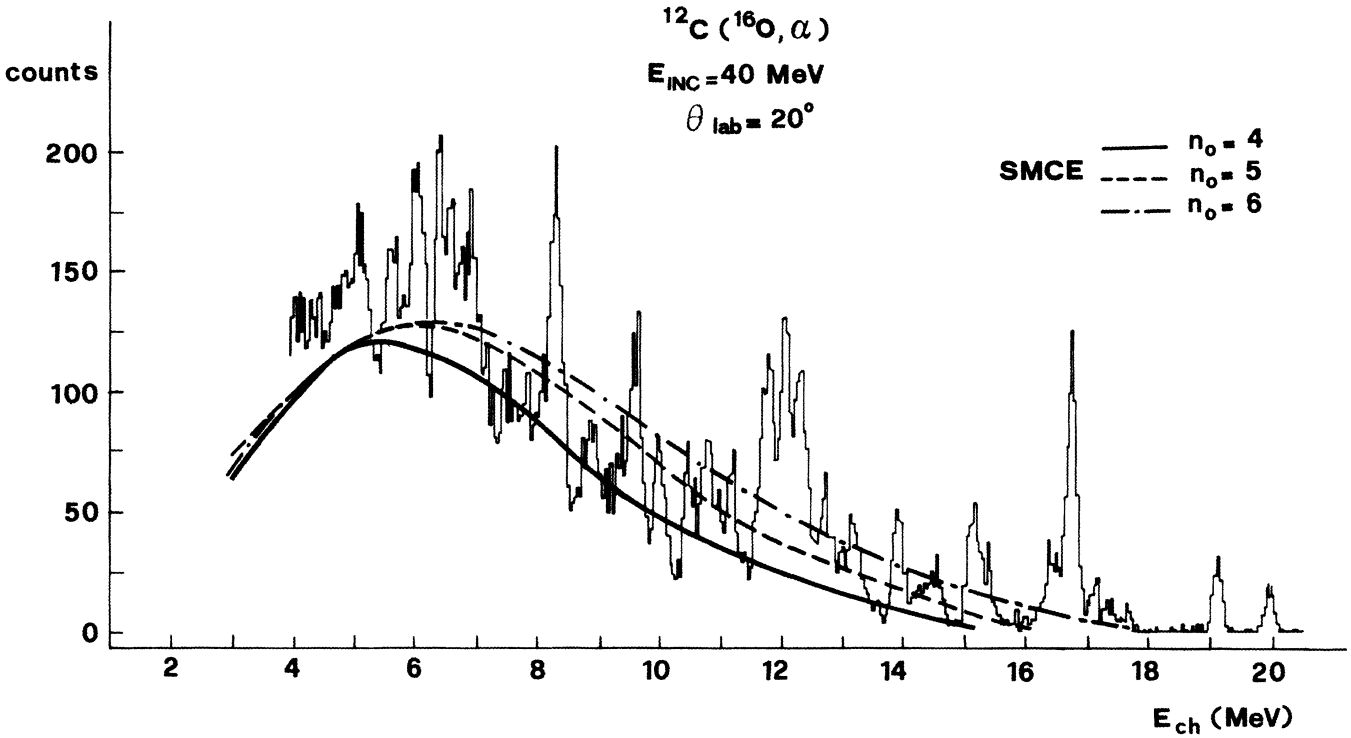

FIG. 6. A complete α spectrum at $E=40$ MeV, $\theta_{lab}=20°$. The results of SMCE calculations with various choices for n_0 are shown.

um "r stage." This is a direct consequence of both the low mass and the moderate excitation energy of the reaction under study, which cause the level density function to be already saturated for the $n=8$ term, which, in accordance with the criterion set forth on p. 468 of Ref. 8, is therefore included in the r stage. This result is perfectly consistent with the information drawn from the fluctuation analysis, i.e., the presence of two (*and only two*) widths. Moreover, at an average intermediate system excitation energy of ~ 31 MeV, the calculated values $\Gamma_6=210$ keV and $\Gamma_r=55$ keV are in agreement with the values extracted by the statistical analysis of experimental data.

B. The average shape of excitation functions

Using the SMCE theory, we calculated the cross sections for the different final levels as a function of incident energy. The results for the two steps are shown in Figs. 4 and 5. Only the precompound $n_0=6$ excitation functions fit the experimental data rather well, while the CN r-term curves are much too steep. Therefore, contrary to the light-ion reaction case,[1] where it was found necessary to add up the two processes, in the present case, at least at the angles considered, the reaction seems to be dominated by emission from the first stage. This is perfectly consistent with the fluctuation analysis, which, where detectable, indicated a very small weight for Γ_2 (Tables I and II).

C. The angular distributions

The angular distributions were carefully measured by Halbert *et al.*[10] and their overall symmetry to 90° has been clearly established. Within this symmetry, however, they exhibit structures which persist after averaging over a quite large (~ 3 MeV) energy range (see Fig. 17 of Ref. 10).

To investigate how these features are reproduced by the different statistical theories, we calculated the angular dis-

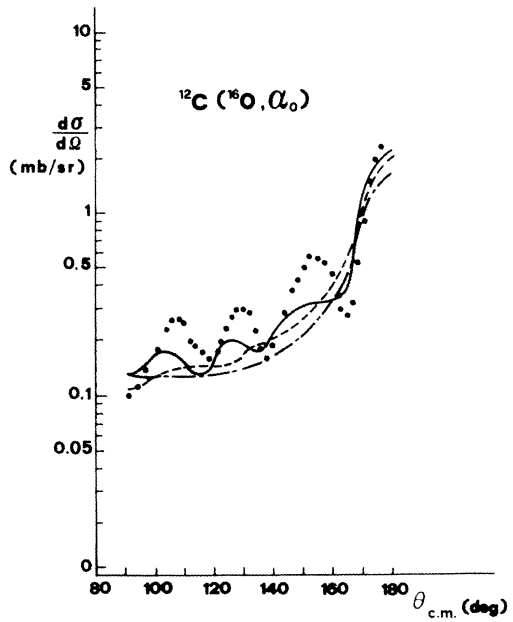

FIG. 7. Angular distribution for the α_0 level averaged from 29.55 to 32.65 MeV (lab) measured by Halbert *et al.* (Ref. 10) (dots) compared with different statistical model predictions: dotted-dashed line, Hauser-Feshbach; dashed line, r term of SMCE; solid line, first step of SMCE.

tribution by means of the Hauser-Feshbach formalism and the SMCE theory.

The results are shown in Fig. 7. Both the Hauser-Feshbach and the r term give smooth angular distributions, while the precompound $n_0=6$ term shows an oscillating behavior much more in agreement with the data. This is not surprising since a system in a precompound configuration certainly has a greater moment of inertia than it would have if completely fused. As was shown in a simple two-l-window model in Ref. 14, this fact brings into the cross section terms with higher l values which may cause conspicuous oscillations in the symmetric angular distributions.

VI. FINAL REMARKS

In addition to the examples already quoted, it is easy to find other cases in the great amount of literature on the $^{12}C(^{16}O,\alpha)$ reaction which show deviations from Hauser-Feshbach predictions, thus implicitly confirming the importance of multistep compound processes.

Average excitation functions for several levels were calculated by Gomez del Campo *et al.*[11] The fits seem quite reasonable; however, more careful study reveals that the theoretical Hauser-Feshbach excitation functions are steeper than the data, although the discrepancy is hardly noticeable due to the very limited energy range ($\sim$3 MeV lab). This behavior is identical to that found for our r-stage calculation (Figs. 3 and 4). This same paper points out the need to introduce an unusually large spin-cutoff value to reproduce the CN coherence widths and their energy dependence: a clear sign of a high moment of inertia of the system, not yet completely fused.

Middleton *et al.*[15] obtained several energy-averaged angular distributions of the $^{16}O(^{12}C,\alpha)$ reaction, which in some cases (e.g., the 0^+ state at $E=6.44$ MeV, the 2^+ state at 7.35 MeV, and others) exhibit oscillations symmetric to 90° similar to those measured by Halbert *et al.*[10] A Hauser-Feshbach calculation was not able to fully account for them.

Very convincing agreement between the experimental and theoretical number of effective fluctuating channels led Singh *et al.*[16] to conclude that the $^{12}C(^{16}O,\alpha)$ reaction from 13.17 to 23.09 MeV is dominated by a statistical process. We want to emphasize that this does not rule out any possible contribution of the SMCE, which is as "statistical" as the classical CN mechanism is believed to be. As was shown in Ref. 17, the variance (which is the reciprocal of the number of effective channels) of the fluctuating cross section is expected to be independent of the particular class of overlapping states being populated.

To summarize, analyses both of already published data and of specific new measurements on spectra and excitation functions indicate the importance and, in some cases, the dominance of multistep compound processes in the $^{12}C(^{16}O,\alpha)$ reaction.

We believe that this mechanism has been widely confused in the past with CN emission. In fact, SMCE also predicts angular distributions symmetric to 90° and fluctuations in excitation functions, whose correlation width might be not dramatically different from the CN one when the multistep chain starts with a not too small number of degrees of freedom, as is the case for light heavy-ion reactions. This mechanism may therefore be easily confused with CN emission when the fluctuation analysis is done with a simple one-class autocorrelation function.

From this standpoint, the cleanest indication of the possible presence of a multistep compound contribution is certainly the scattering of Γ values extracted for various levels and/or angles.

An important result of the present analysis is also the information supplied on the nature of the overlapping doorway states populated in the reaction. It was shown above that an α cluster configuration of such doorway states does seem highly plausible. Such a picture was suggested earlier by several authors[18] to explain the intermediate resonances found in excitation functions measured in the interaction of "α nuclei" (e.g., ^{12}C, ^{16}O). It was stressed that the above hypothesis had not yet been reinforced by quantitative calculations.[19] Our paper, by presenting a new point of view, should make a step forward toward this goal.

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