# Emission of alpha particles in statistical multistep compound reactions

R. Bonetti, L. Colli Milazzo, R. Landini, and M. Melanotte
*Istituto di Fisica Generale Applicata, Università di Milano, Milano, Italy*

A. De Rosa, G. Inglima, E. Perillo, and M. Sandoli
*Istituto di Fisica Sperimentale, Università di Napoli, Napoli, Italy*

F. Shahin
*Physics Department of the University of Mansoura, Mansoura, Egypt*
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Excitation functions and angular distributions of alpha particles emitted from the $^{27}$Al($^3$He,$\alpha$) and $^{27}$Al(p,$\alpha$) reactions are measured at a composite nucleus excitation energy of about 30 MeV. The experimental results together with the widely varying correlation widths extracted from the fluctuation analysis are successfully interpreted on the basis of the statistical multistep compound emission mechanism. Confirmation is found of the interpretation of each experimental correlation width in terms of a coherent sum of the widths of the relevant stages of the reactions, previously proposed in the case of proton channels. Moreover, the $\alpha$-spectrum shape and the correlation width values are shown to be consistent with an $\alpha$ preformation picture of the target nuclei considered.

[NUCLEAR REACTIONS $^{27}$Al($^3$He,$\alpha$) $E=8.2-13$ MeV; $^{27}$Al(p,$\alpha$), $E=18.5-25.6$ MeV; measured $\sigma(E;\vartheta)$; statistical multistep compound emission, calculated $\sigma(E)$, $\sigma(E_\alpha)$; generalized autocorrelation analysis, extracted coherence widths; suggested $\alpha$ preformation.]

## I. INTRODUCTION

The aim of this paper is to discuss the emission mechanism of alpha particles in a few reactions of the ($^3$He,$\alpha$) and (p,$\alpha$) type involving the target nuclei $^{27}$Al and $^{25}$Mg. The problem of alpha emission is one that is widely discussed. In the case of (p,$\alpha$) reactions, for instance, two mechanisms have been commonly considered, the triton pickup and the preformed $\alpha$-particle knockout. The former is generally used in the analysis of alpha peaks corresponding to low-lying residual nucleus levels, whose asymmetric angular distribution can be reproduced on the basis of the one-step triton pickup hypothesis.[1] On the other hand, in the calculation of the continuum alpha spectra due to precompound emission, the hypothesis of preformed alpha particle knockout has usually been used, even though always within the framework of the semiclassical exciton or hybrid models.[2,8] The triton pickup mechanism is also used by Tamura *et al.* to explain continuum alpha spectra from some (p,$\alpha$) reactions (on Fe and Nb) in the framework of their multistep direct reaction theory.[3]

At the present time it is difficult to obtain unambiguous information about the $\alpha$-emission mechanisms and their possible different fields of application depending on the incident energy, target nucleus, and type of reaction. However, the problem underlying this research, i.e., determination of the preexistence of alpha particles in nuclei (or in some of them), seems so important that it is definitely worthwhile continuing this line of research. For this purpose we measured the following:

(a) the spectrum of emitted $\alpha$ in the $^{25}$Mg($^3$He,$\alpha$) reaction at a $^3$He incident energy of 12 MeV and an emission angle of 120°;

(b) the excitation functions corresponding to a number of residual nucleus low-lying levels in an incident energy interval from 8.2 to 13 MeV for the $^{27}$Al($^3$He,$\alpha$) reaction;

(c) the $^{27}$Al(p,$\alpha$) excitation functions of several residual nucleus levels for an incident proton energy from 18.5 to 25.6 MeV.

All these excitation functions were taken simultaneously at different emission angles. We are also completing here the discussion of the $^{25}$Mg($^3$He,$\alpha$) reaction measured before.[4]

It is worth noting that the two reactions $^3$He + $^{25}$Mg and p + $^{27}$Al form the same composite nucleus at the same excitation energy, about 30 MeV. All the above results were analyzed in the framework of the fully quantum-mechanical statistical multistep compound theory[5] (SMCE), following the work done earlier on ($^3$He,p) reactions with the same targets.[4,6] This mechanism was selected on the basis of the emitted alphas's angular distribution, which is usually symmetric to 90°, and because of the striking presence of very wide fluctuations in the excitation functions which, as in the case of emitted protons,[4,6] show a compoundlike statistical process.

## II. DESCRIPTION OF THE EXPERIMENTS

The excitation functions of the $^{27}$Al($^3$He,$\alpha$) reaction were measured at the CN Van de Graaff accelerator belonging to LNL in Legnaro. The experimental apparatus was the same as that used before and described for the previously published $^{25}$Mg($^3$He,$\alpha$) reaction,[4] except that the number of detectors employed simultaneously was in-

 

creased from two to five. We therefore simultaneously detected the $\alpha$-particle spectra at laboratory angles of 60°, 80°, 100°, 120°, and 140°, at incident energy steps of 75 keV. For these measurements we used surface barrier Si detectors just thick enough to stop the most energetic $\alpha$ particles (300—400 $\mu$). The complete $\alpha$ spectrum taken at 12 MeV for the $^{25}$Mg target was obtained with a telescope of detectors that allowed mass separation by means of the standard $\Delta E/E$ technique. The thickness of the $^{27}$Al and $^{25}$Mg targets was about 100 $\mu$, which gave rise to an energy spread of about 20 keV in the incident channel. The $^{27}$Al(p,$\alpha$) measurements were taken with the Milan AVF Cyclotron with $\alpha$ detectors, similar to those described above, placed at 30° and 150°, in 100 keV incident proton energy steps. In this case, due to the non-negligible energy spreading of the cyclotron beam, the resolution in the incident channel was about 50 keV. A typical $\alpha$ spectrum is shown in Fig. 1.

## III. INTERPRETATION OF THE RESULTS

### A. Reactions initiated by $^3$He

The characteristics of the results under discussion for interpretation are the following:

(1) emitted $\alpha$-spectrum shape;
(2) angular distribution;
(3) average shape of the excitation function curves;
(4) fluctuation characteristics.

#### *1. Spectrum shape*

Application of the SMCE theory for calculation of the $\alpha$-particle spectrum of the $^{25}$Mg($^3$He,$\alpha$) reaction is shown in Fig. 2. In this calculation, using information taken from the previous work on ($^3$He,p) reactions, we assume that the initial number of excitons produced in the intermediate composite nucleus is five, as a consequence of the destruction of the incident $^3$He at the first interaction with a target nucleon, which therefore remains excited and also produces a hole in the nucleus. As the SMCE theory assumes, all these excitons must be bound.

The $\alpha$ particle is emitted as a consequence of a second interaction, in which it is treated as one exciton. This is a basic assumption which we are introducing in the application of the theory; physically it means that the $\alpha$ particle must be found preformed and excited like one nucleon in the first or second interaction. There are a few remarks to be made in favor of this point. The most important quantity determining the shape of the emitted $\alpha$ spectrum is the residual nucleus level density, which in the SMCE theory is given by three contributions (see formulae 5.16, 5.17, and 5.18 of Ref. 5): one corresponding in our case to the level density of six excitons, one of which is an $\alpha$ hole; the second (the most important in relative value) corresponding to four excitons, one of which is also an $\alpha$ hole; and a third much smaller one with only two excitons.

As for the nucleon hole, the maximum energy variation allowed for the $\alpha$ hole in each point of the spectrum is the excitation energy $U$ of the residual nucleus, which in our case reaches a maximum value of 14 MeV at the extreme left-hand end of the spectrum. We first observe that throughout the spectrum this variation is not very large, especially in consideration of the fact that this maximum energy in the most frequent cases is divided among five excitons. This fact makes it possible to neglect any possible energy dependence of the $\alpha$-nucleon interaction in calculating the damping and escape widths of the SMCE cross section. We note, however, that the effective nucleon-nucleon interaction (from which the $\alpha$-nucleon

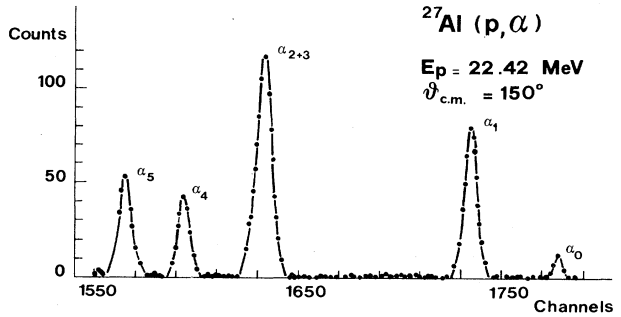


FIG. 1. A typical alpha spectrum from the $^{27}$Al(p,$\alpha$) reaction taken at $\vartheta_{c.m.}=150°$.

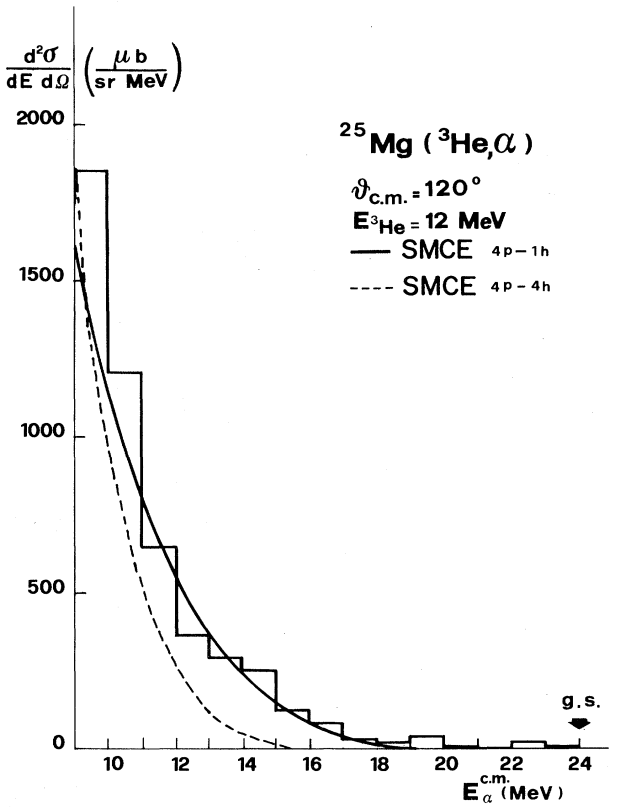


FIG. 2. Experimental and calculated spectra at $\vartheta_{c.m.}=120°$ for the $^{25}$Mg($^3$He,$\alpha$) reaction. The calculation was done assuming two different initial exciton numbers.

one can be obtained by averaging over the density of the $\alpha$ particle) has been found to be practically energy independent in the region of interest here.[17]

The functions $P(U)$ as given in Ref. 5 and used in our calculations have been figured by assuming, as is usually done, constant single particle level density (an equidistant level model) for all the "normal" excitons and for the $\alpha$ hole, too. This last point is an assumption, because nothing is known about the $\alpha$-hole level density. We now consider what the effect of a different energy dependence of the $\alpha$-hole level density would be. A level density function that increased with the energy $U$ would lead to a steeper spectrum shape than the one calculated in the constant level density assumption, a spectrum that could be interpreted as being due to emission from a stage with a higher exciton number, so that $\alpha$ preformation would not be deduced. But this is not the experimental case.

An $\alpha$-hole level density that decreased as energy increased would lead to a less steep spectrum shape than the one calculated. This case might result in a spectrum shape similar to the experimental one in the event of a preexisting $\alpha$ particle emitted from a stage with a higher number of excitons, if the combined effects of greater steepness due to the higher number of excitons and of decreasing $\alpha$-hole level density were to cancel each other out. But in this case, too, it is necessary to assume a preformed $\alpha$ particle and an $\alpha$ hole in the nucleus.

We now consider other possibilities of $\alpha$ emission without the assumption of $\alpha$ preformation. The first case is the formation of the $\alpha$ particle during emission from the nucleus by means of triton or $^3$He pickup as is usually considered in the direct effect. This would leave three more excitons in the residual nucleus, giving rise to a much steeper spectrum than the experimental one, as shown in Fig. 2. In the more general hypothesis that the alpha particle could be formed by successive interactions of an excited particle with other excited or nonexcited nucleons or else by a particular kind of triton pickup where the triton consists in part of excited nucleons, it would never be possible, starting from the five-exciton stage (four particles and one hole), which as stated above is considered the initial stage, to reach a final stage with six or four excitons, as given by the calculated spectrum. In our opinion, what makes this kind of emission improbable is the experimental fact that the $\alpha$ spectrum has exactly the same shape as the proton spectrum emitted in the same reaction (see Fig. 5 of Ref. 4) when compared at the same residual nucleus excitation energy. This seems to indicate a very similar emission mechanism acting for $\alpha$ and proton emission.

For all these reasons we assume that the $\alpha$ particle in the nucleus has behavior similar to that of a proton and that it leaves behind an $\alpha$ hole like an "exciton." Of course, to determine the absolute value of the cross section for $\alpha$ emission, more knowledge would be required about the $\alpha$-preformation probability and about the $\alpha$-hole level density, so this will not be discussed herein.

As was done for the proton spectrum[4] in the calculations, mainly for the sake of simplicity, we used the original formulation of the SMCE theory as given in Ref. 5, where the wave functions describing the interacting particles are taken to be constant within the nuclear volume. However, we found that the use of more realistic wave functions does not change the shape of the spectrum, although it is important for the absolute value of the cross section.[7]

As for the protons, the calculations show that the five-exciton stage is the first and only one active in the precompound chain; the next stage must be included in the equilibrium $r$ stage (see Fig. 7 of Ref. 7).

### 2. *Angular distribution*

The angular distribution predicted by the SMCE is symmetric to 90° and can be calculated using formula (5.1) of Ref. 5. The calculations show that in the case of a transition to discrete states, the angular distribution of particles originating from emission from the five-exciton stage is practically the same as the one from the $r$ stage for the cases considered here. It therefore does not depend

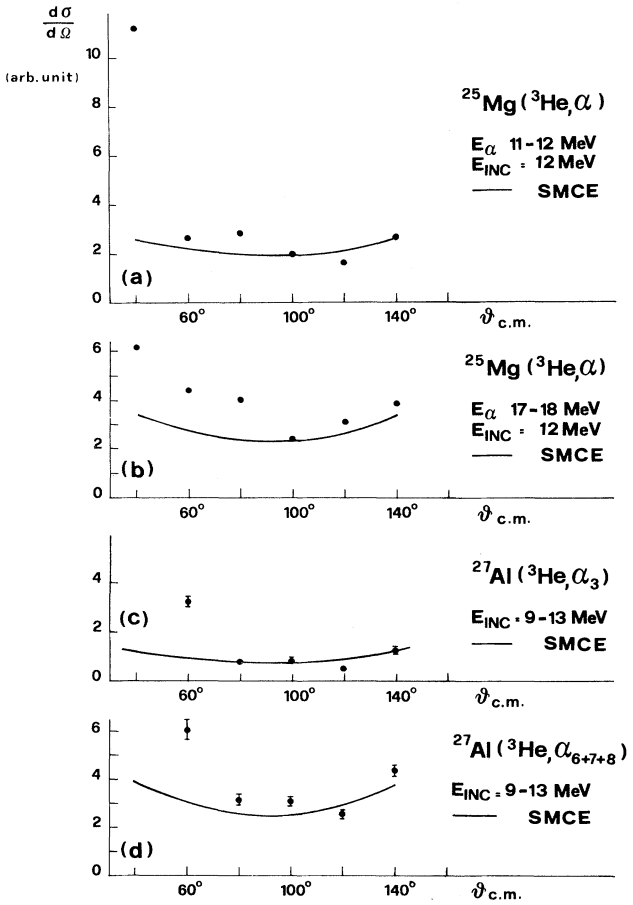


FIG. 3. Experimental and calculated angular distributions from the following reactions: (a) and (b) $^{25}$Mg($^3$He,$\alpha$) integrated over 1 MeV of the outgoing alpha energy (the errors are within the dimension of the points); (c) and (d) $^{27}$Al($^3$He,$\alpha$) averaged over 4 MeV of the $^3$He incident energy. The angular distributions correspond to two different final groups.

on the possible different mixture of the two contributions. Studies of the angular distribution of particles whose excitation functions show pronounced fluctuations, as in the present case, must be done only on angular distributions averaged over either the incoming or the exit energy, in order to avoid the interference effect that would destroy the 90° symmetry.

Figure 3 parts (a) and (b) show two cases of angular distributions taken from the $^{25}$Mg($^3$He,$\alpha$) reaction averaged over 1 MeV of the $\alpha$-kinetic energy at a fixed incoming energy. The curve taken at a higher emission energy shows some contributions from a probable direct effect in the forward direction. The other curve shows more agreement with the theory. Small deviations can be attributed to insufficient averaging. Similar results are shown in Fig. 3 parts (c) and (d) for the $^{27}$Al($^3$He,$\alpha$) reaction, where the angular distributions correspond to definite final nucleus levels and the averaging is done over the energy of the incoming particle. Similar behavior is shown in Table I for the $^{27}$Al(p,$\alpha$) reaction. These cross-section values obtained in a previous experiment at $E_p = 36.5$ MeV (Ref. 8) do in fact point out the substantial isotropy of the angular distribution for angles above 60°.

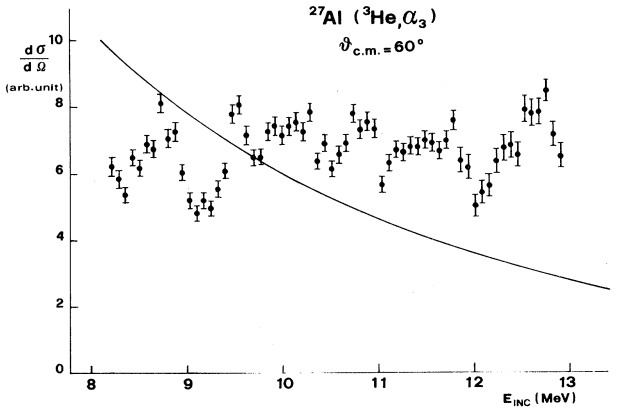


FIG. 4. Excitation function of the $^{27}$Al($^3$He,$\alpha_3$) transition at $\vartheta_{c.m.} = 60°$ as an example of transition at a forward angle dominated by the direct effect. This is shown by the deviation between the theoretical average excitation function calculated with the SMCE and the experimental curve.

### 3. *Average shape of the excitation function curves*

Average excitation functions were calculated theoretically in the framework of the SMCE mechanism as described in the previous work on ($^3$He,p).[4] Only excitation functions taken in a backward direction were considered in order to avoid the presence of the direct effect as much as possible. The direct effect is in fact shown in Fig. 4, which is an example of a forward angle transition. For this reason we only analyzed the excitation functions of $^{27}$Al($^3$He,$\alpha$) at 120° and 140° [Fig. 5 parts (a) and (b)]. On the basis of the results obtained from the spectrum analysis, contributions from two stages were taken into consideration, the five-exciton one ($\sigma_5$) and the $r$ stage ($\sigma_r$). The relative contribution made by each of the two steps is unknown *a priori* because it depends on the details of the structure of the residual nucleus state involved, which is almost unknown. Therefore the relative cross sections and the normalization factor remain free parameters. They are found by means of successive trials, requiring that the same percentage of $\sigma_5/\sigma_r$ be able to describe the fluctuation characteristics, i.e., the correlation width for each final level (this is analyzed in the next section).

For the normalization factor of the average curve the one giving the lowest square deviation value was always chosen. It must be noted that for this calculation we used the explicit formula describing the transition to the continuum (formula 5.1 of Ref. 5). This formula is obviously summed over many final states. We adapted it in order to use it to calculate a transition to only one final level, excluding the sum over the final state angular momenta and dividing it by the number of levels at a given residual excitation energy value. Of course the transition to the ground state could not be calculated in the framework of this approximation, which gives rise to a zero-value cross section. In this particular case we therefore took a fictitious residual excitation value of 1 MeV. Due to these approximations, these average excitation curves represent an approximate description in which only the shape has a correct meaning in connection with variation of the composite nucleus excitation energy. The same kind of analysis was applied to the previously measured $^{25}$Mg($^3$He,$\alpha$) reaction.[4] In the case of the two transitions $^{25}$Mg($^3$He,$\alpha_0$) and $^{25}$Mg($^3$He,$\alpha_1$) where the excitation functions extend to 20 MeV, even at these backward angles in the last part of the curve it is necessary to consider the presence of a direct effect (neutron pickup) which is shown by the flat shape of the excitation function. An angular distribution taken at 18 MeV of the $^3$He incident beam clearly confirms the presence of a direct effect. A calculation was developed on the basis of a DWBA theory in the framework of the neutron pickup mechanism. For this purpose conventional methods were used. The $^3$He and alpha distorted waves were generated by means of the Perey optical model parameters.[9] The form factor is given by a Woods-Saxon volume potential, calculated for the $1d_{5/2}$ picked-up neutron by means of the energy separation method. The bound state geometrical parameters are the same as the best fitting ones reported in a paper on the same reaction at 33 MeV by Dehnhard *et al.*[10] All these quantities are shown in Table II.

TABLE I. Cross-section values for the $^{27}$Al(p,$\alpha$) reaction at $E_p = 36.5$ MeV (Ref. 8), integrated from $E_\alpha = 10$ MeV.

| $\vartheta$ | $\sigma(\vartheta)$ (mb/sr) |
|---|---|
| 30° | 7.67 |
| 60° | 4.59 |
| 90° | 4.348 |
| 120° | 4.269 |

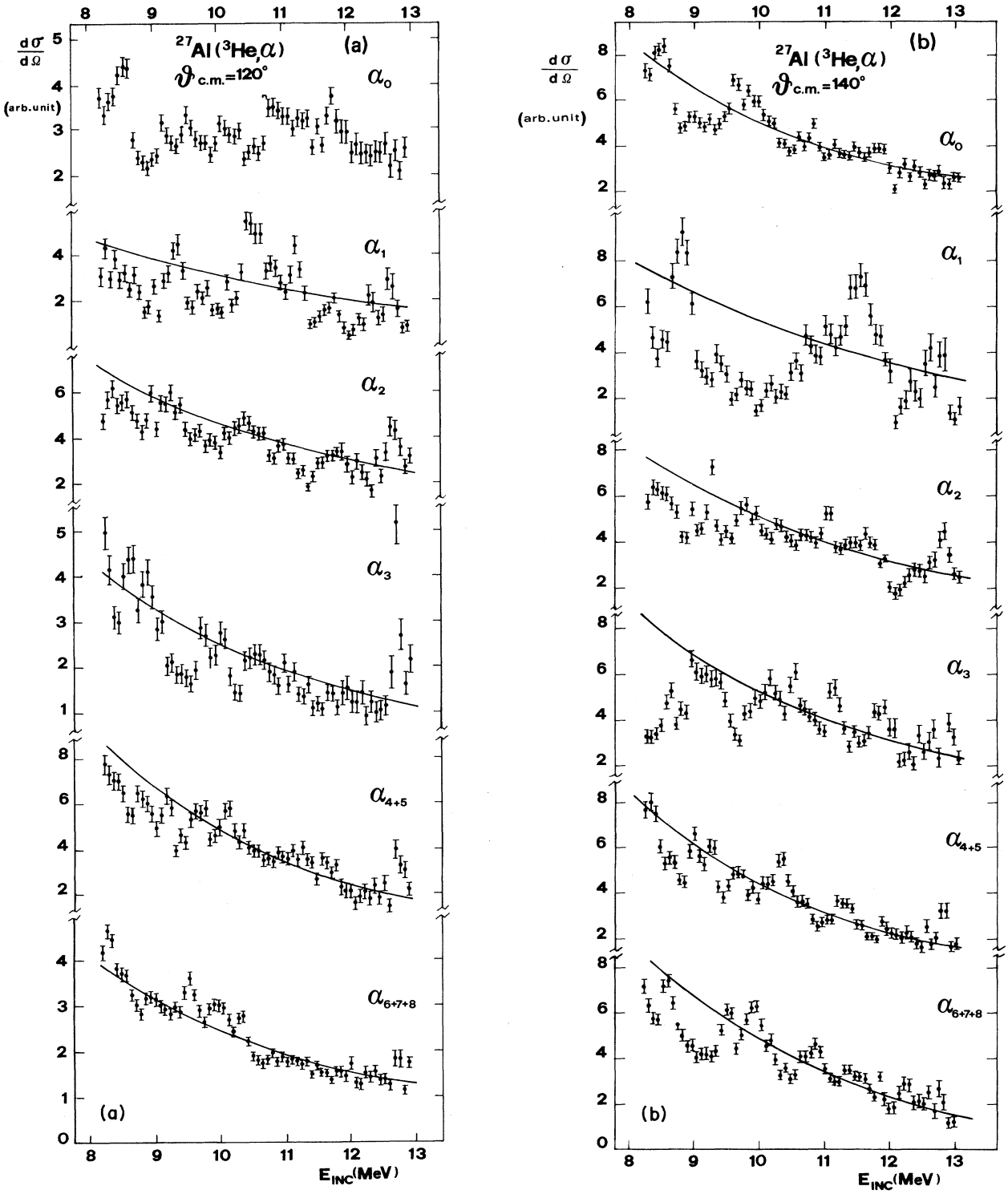


FIG. 5. Excitation functions of the $^{27}$Al($^3$He,$\alpha$) reaction at $\vartheta_{c.m.}=120°$ (a) and 140° (b). The curves are the results of the SMCE calculations (see the text).

Because of the zero-range and other approximations used in the calculations, we could not expect to reproduce the absolute value of the cross section. Nevertheless, a good estimate can be made by looking at the reduction of the amplitude of the fluctuations as soon as the direct effect becomes important. This allows extraction of the fraction $Y_d$ of this effect to the total cross section. Using this number calculated elsewhere,[11] we obtain an *a priori*

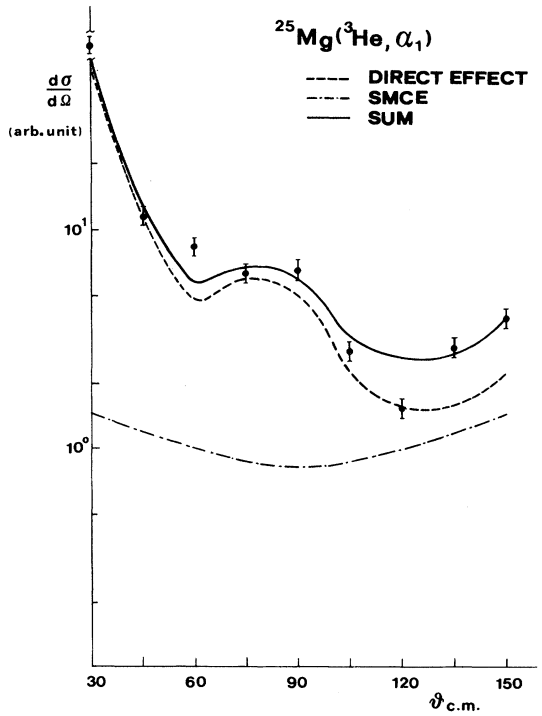


FIG. 6. Experimental and calculated angular distributions for the $^{25}Mg(^3He,\alpha_1)$ transition. The curve marked "sum" is obtained by adding to the SMCE calculation a direct effect contribution estimated as explained in the text.

criterion for mixing the direct effect and the SMCE which enables us to calculate both the excitation functions and the angular distributions in these "mixed" situations. The result for the angular distribution is shown in the case of the $\alpha_1$ transition in Fig. 6; the corresponding result for the excitation function is shown in Fig. 7; in the 16–20 MeV range this result is dominated by the direct effect, even though fluctuations are still detectable due to the simultaneous presence of some multistep compound emission. In fact, it is well known that fluctuations are only slightly reduced by the substantial presence of a nonfluctuating direct effect component.[12] All the other excitation functions can be fitted by considering different contributions from the $\sigma_5$ and $\sigma_r$ stages except the $^{27}Al(^3He,\alpha_0)$ transition at 120°, where the very flat shape can again be attributed to the presence of a direct effect component. In this case we preferred to simply use an empirically constructed least square average curve. The results of this analysis are shown in Tables III and IV.

### 4. *Analysis of fluctuation width*

Two methods were used to extract the fluctuation widths ($\Gamma$) present in the excitation functions discussed above: the spectral density method, recently developed by De Rosa *et al.*,[13] and direct analysis of the autocorrelation function done with the generalized autocorrelation function developed by Friedman *et al.*[14] in the framework of their nested-doorway model of multistep compound reactions.

Because of the similarities between the nested-doorway model and the SMCE theory, the generalized autocorrelation function is applied here, even though some approximations are different, on the assumption that the predictions for the fluctuating behavior should not vary much. The basic assumption as well as the application of these methods to the experimental data were described in detail in previous papers[4,6,15] and are not being repeated here. We only want to point out that in both the methods used, analysis of the fluctuation excitation functions starts with determination of an average excitation function and construction of an autocorrelation function. Only backward angles (120° and 140°) were selected because they are expected to be free of any direct effect contribution. The average excitation functions are the ones described above, calculated theoretically as a mixture of $\sigma_5$ and $\sigma_r$. This is true of all the transitions except the $^{25}Mg(^3He,\alpha_0)$ and $^{25}Mg(^3He,\alpha_1)$ transitions at the higher energies and the $^{27}Al(^3He,\alpha_0)$ at 120°, as already shown. Then the autocorrelation function is constructed for each case considered. That we are dealing with true statistical fluctuations is shown by the lack of correlation between the curves corresponding to the different final levels or to different angles. The autocorrelation functions obtained in this way are shown in Figs. 8 and 9 together with the theoretical shape of the generalized autocorrelation functions constructed with the same mixture of the two contributions ($\sigma_5$ and $\sigma_r$) used in calculating the average curves. The two corresponding widths $\Gamma_5$ and $\Gamma_r$ (230 and 50 keV) used in this calculation are roughly the average $\Gamma$ values given directly by the spectral density method. They are also the same widths found in the fluctuation analysis of proton channels[4] and correspond nicely to the theoretical calculations of $\Gamma_5$ and $\Gamma_r$ done on the basis of

TABLE II. Optical model parameters used for the DWBA calculations of the $^{25}Mg(^3He,\alpha_0-\alpha_1)$ transitions.

| | $V_R$ (MeV) | $r_{0R}$ (fm) | $a_R$ (fm) | $W_1$ (MeV) | $r_{01}$ (fm) | $a_1$ (fm) | $r_c$ (fm) |
|---|---|---|---|---|---|---|---|
| Entrance channel | 150 | 1.26 | 0.63 | 26 | 1.38 | 1.1 | 1.4 |
| Exit channel | 215 | 1.24 | 0.67 | 61.9 | 0.94 | 0.22 | 1.7 |
| Bound state | 52.93 | 1.25 | 0.65 | | | | |

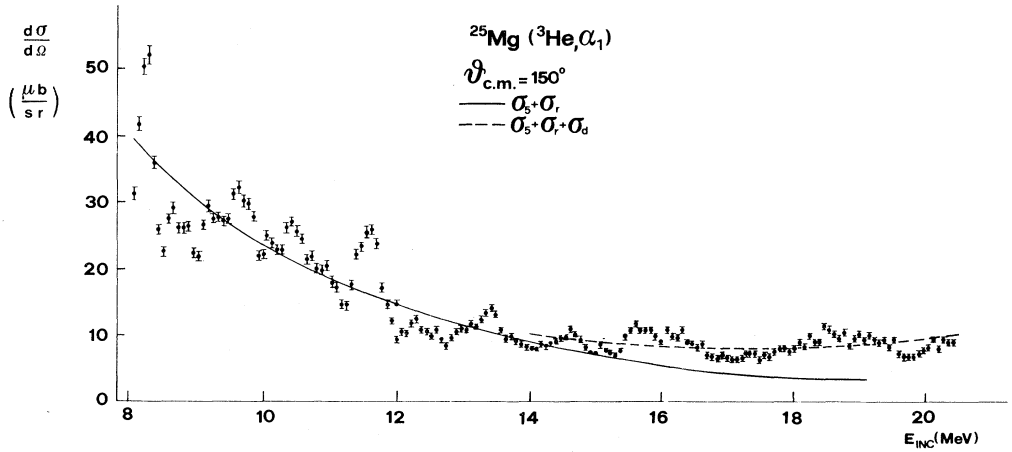


FIG. 7. Excitation function at $\vartheta_{c.m.}=150°$ for the $^{25}$Mg($^3$He,$\alpha_1$) transition. The theoretical curve is calculated with a mixture of precompound and compound nucleus contributions ($\sigma_5=90\%$, $\sigma_r=10\%$). In the 14—20 MeV energy range the result is also shown that is obtained by adding a direct effect contribution equal to 50% of the total cross section at the middle of the range considered (see the text).

the SMCE.[7] It seems worthwhile to emphasize the importance of the above agreements, since they supply additional support for the $\alpha$-preformation hypothesis.

Tables III and IV show all the results of the fluctuation analysis of the reactions initiated by $^3$He. It may be worth pointing out the overall consistency of the relative cross-section values extracted by means of the various independent methods of analysis. As a final comment, we note that the large variation of $\Gamma$ values for different final channels, which had already been pointed out in previous papers,[4,6] is confirmed here. This fact, in addition to the interpretation of the reaction mechanism by means of the SMCE, led us to interpret each experimental $\Gamma$ value by means of a mixture of two widths, with different weights due to the different structure of each final state. Moreover, the results obtained for the reaction undoubtedly confirm that no isospin dependence of $\Gamma$ can be invoked to explain the effect discussed above. This conclusion is drawn from the results obtained for the $\alpha_1$ level whose isospin value is $T=1$. According to a result obtained by Bizzeti[16] in the classical one-level case this would lead to a reduction in the $\Gamma$ value. On the contrary, the $\Gamma$ value for the $\alpha_1$ level turns out to be the largest.

### B. Reaction initiated by protons

The $^{27}$Al(p,$\alpha$) reaction requires some comment. The main difference between this reaction and the ones initiated by $^3$He is the possibility that a three-exciton stage may be formed in the first interaction of the incoming protons,

TABLE III. Results obtained from the fluctuation analysis of the $^{25}$Mg($^3$He,$\alpha$) excitation functions. Column 6 shows the mean square deviation coefficients obtained from the various alpha groups analyzed. In column 7 the relative cross sections for precompound emission $\sigma_{pc}/\sigma_{tot}$ used to fit the average excitation functions are shown. They should be compared with those obtained with the spectral density method (column 8) and with the generalized autocorrelation function analysis (column 9). The widths of the precompound ($\Gamma_{pc}$) and compound nucleus ($\Gamma_r$) states as resulting from the spectral density analysis are shown in the last two columns.

| Peak | Excitation energy (MeV) | $J^\pi$ | Incident energy range analyzed (MeV) | Angle | $C(0)_{exp}\pm\Delta C(0)$ | Relative cross sections $\sigma_5/\sigma_{tot}$ Average excitation function | Spectral density | Generalized autocorrelation function | $\Gamma_5$ (keV) | $\Gamma_r$ (keV) |
|---|---|---|---|---|---|---|---|---|---|---|
| $\alpha_0$ | 0. | $0^+$ | 12—20.425 | 150° | 0.07 ±0.014 | 0.60±0.05 | 0.64±0.033 | 0.60±0.05 | 162 | 40 |
| $\alpha_1$ | 1.37 | $2^+$ | 8—20.425 | 150° | 0.027±0.007 | 0.82±0.05 | 0.82±0.067 | 0.90±0.05 | 154 | 45 |
| $\alpha_{2+3}$ | 4.12—4.24 | $4^+$-$2^+$ | 8—16 | 150° | 0.013±0.003 | 0.82±0.05 | 0.82±0.028 | 0.82±0.05 | 253 | 45 |
| $\alpha_4$ | 5.24 | $3^+$ | 8—16 | 150° | 0.017±0.003 | 0.70±0.05 | 0.83±0.025 | 0.70±0.05 | 248 | 31 |

TABLE IV. Same as Table III for the $^{27}Al(^{3}He,\alpha)$ reaction.

| Peak | Excitation energy (MeV) | $J^{\pi}$ | Incident energy range analyzed (MeV) | Angle | $C(0)_{exp}\pm\Delta C(0)$ | Relative cross sections $\sigma_5/\sigma_{tot}$ Average excitation function | Spectral density | Generalized autocorrelation function | $\Gamma_5$ (keV) | $\Gamma_r$ (keV) |
|---|---|---|---|---|---|---|---|---|---|---|
| $\alpha_0$ | 0. | $5^+$ | 8.20–13 | 120° | 0.0248±0.0075 | | 0.73±0.05 | 0.70±0.05 | 285±28 | 45±17 |
| | | | | 140° | 0.021 ±0.006 | 0.60±0.05 | 0.76±0.05 | 0.60±0.05 | 236±29 | 55±17 |
| $\alpha_1$ | 0.228 | $0^+$ | 8.20–13 | 120° | 0.18 ±0.06 | 1.0 ±0.05 | 0.85±0.07 | 1.0 ±0.05 | 246±31 | 48±23 |
| | | | | 140° | 0.20 ±0.08 | 1.0 ±0.05 | 0.83±0.07 | 1.0 ±0.05 | 289±34 | 45±26 |
| $\alpha_2$ | 0.416 | $3^+$ | 8.20–13 | 120° | 0.051 ±0.016 | 0.80±0.05 | 0.64±0.064 | 0.80±0.05 | 218±28 | 45±13 |
| | | | | 140° | 0.045 ±0.015 | 0.80±0.05 | 0.57±0.04 | 0.80±0.05 | 113±18 | 55±26 |
| $\alpha_3$ | 1.057 | $1^+$ | 8.20–13 | 120° | 0.071 ±0.02 | 0.70±0.05 | 0.69±0.04 | 0.70±0.05 | 165±26 | 43±17 |
| | | | | 140° | 0.071 ±0.02 | 0.70±0.05 | 0.71±0.04 | 0.70±0.05 | 267±28 | 39±13 |
| $\alpha_{4+5}$ | 1.759–1.85 | $2^+$-$1^+$ | 8.20–13 | 120° | 0.048 ±0.013 | 0.45±0.05 | 0.75±0.05 | 0.45±0.05 | 142±29 | 51±26 |
| | | | | 140° | 0.025 ±0.007 | 0.45±0.05 | 0.57±0.03 | 0.45±0.05 | 190±28 | 55±13 |
| $\alpha_{6+7+8}$ | 2.068–2.069<br>2.071 | $4^+$-$2^+$-$1^+$ | 8.20–13 | 120° | 0.014 ±0.004 | 0.90±0.05 | 0.77±0.05 | 0.90±0.05 | 205±30 | 54±24 |
| | | | | 140° | 0.02 ±0.007 | 0.90±0.05 | 0.76±0.05 | 0.90±0.05 | 206±23 | 42±14 |

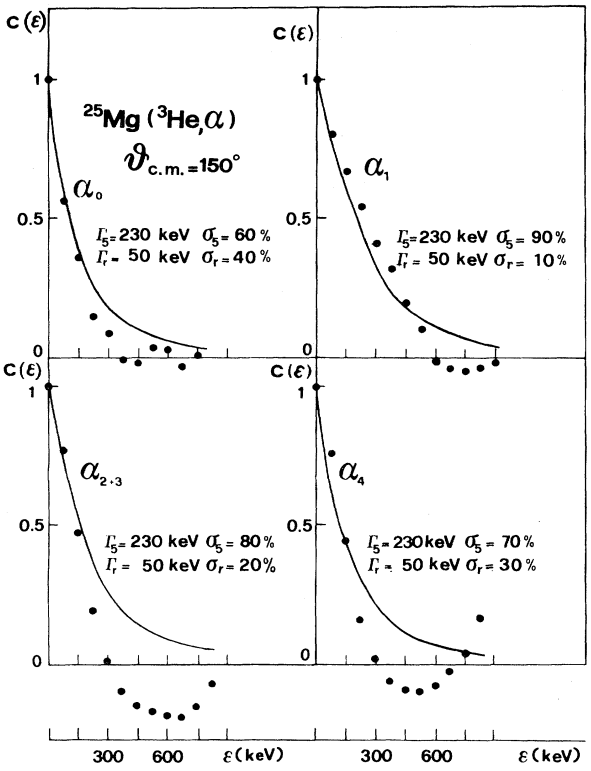


FIG. 8. Relative autocorrelation function analysis of the measured alpha transitions for the $^{25}$Mg($^3$He,$\alpha$) reaction (points) together with the theoretical curves obtained from the generalized autocorrelation function (Ref. 14). The relative cross sections and the widths used in each case for the theoretical calculation are indicated.

a stage which was not found in the $^3$He initiated reactions (see the discussion on spectrum shape). This point is particularly important for the transition to the final nucleus ground state. Indeed this particular transition must leave the residual nucleus without excitons, which in the SMCE framework means that, of the three ways in which a particle can be emitted from a certain state, only the one with a reduction in the number of excitons can be considered (see formulae 5.16, 5.17, and 5.18 of Ref. 5). The reaction is therefore described as follows: The incoming proton excites a nucleon, forming a three-exciton state (two particles, one hole) and then the successive interaction between the two excited particles ejects one of them, removing all the energy from the state. It is obvious that any other kind of interaction either increasing or leaving unchanged the number of excitons cannot be used to describe a transition to the ground state. In the case analyzed here, the emission of an $\alpha$ particle is possible from the first stage (three excitons) only if an alpha is found preformed in the nucleus and then emitted by a second interaction with the proton, which gives up all its energy. A consequence of this $\alpha$ emission from the three-exciton stage should be a fluctuating excitation function showing a $\Gamma$ value larger than the one found for cases when the initial stage was characterized by five excitons (see the $^3$He initiated reactions). The fluctuation analysis is therefore very important in order to get information on the $\alpha$-emission mechanism from this reaction.

Here we obtain the same composite $^{28}$Si nucleus formed in the $^{25}$Mg($^3$He,$\alpha$) reaction analyzed above. The excitation energy is also about the same (30 MeV). It is therefore simple to calculate the $\Gamma$ value expected in the case discussed above. Its predicted value, using the same parameters which made it possible to reproduce the $\Gamma_5$ and $\Gamma_r$ values,[7] turns out to be about 380 keV. The analysis of the excitation curves and their fluctuations is done in the same way as discussed above. An average excitation function is obtained theoretically by combining the emission contributions from various stages. The experimental result at 150°, together with the theoretical calculations, is shown in Fig. 10. Figure 11 shows an example of an excitation function at a forward angle.

In this case of (p,$\alpha$) three contributions are possible: from the three, five, and $r$ stages. Considering the rather large errors affecting all the methods of analysis, it is almost impossible to make a real distinction among three contributions. Therefore, because of its sensitivity, we look first at the results of the spectral density fluctuation analysis to see if some of the transitions to final nucleus levels are dominated by one of the expected $\Gamma$'s. The results are shown in Table V. The largest value for the coherence width is found in the transition to the ground state, which does really seem to be dominated by a $\Gamma$ value of about 300 keV. This value must be corrected for

TABLE V. Same as Table III for the $^{27}$Al(p,$\alpha$) reaction. The values shown in column 10 correspond to $\Gamma_5$, except for the ground state transition ($\alpha_0$), where the experimental coherence width is interpreted as $\Gamma_3$.

| Peak | Excitation energy (MeV) | $J^\pi$ | Incident energy range analyzed (MeV) | Angle | $C(0)_{exp}\pm\Delta C(0)$ | Relative cross sections $\sigma_{pc}/\sigma_{tot}$ Average excitation function | Spectral density | Generalized autocorrelation function | $\Gamma_{pc}$ | $\Gamma_r$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $\alpha_0$ | 0. | $0^+$ | 18.52–24.12 | 30° | 0.06 ±0.023 | | 0.73 | 0.85 | 300 | 50 |
| | | | 18.52–25.62 | 150° | 0.14 ±0.05 | | 0.72 | 0.85 | 304 | 50 |
| $\alpha_1$ | 1.37 | $2^+$ | 18.52–25.62 | 150° | 0.067±0.02 | 0.80 | 0.68 | 0.80 | 203 | 50 |
| $\alpha_{2+3}$ | 4.12–4.24 | $4^+$-$2^+$ | 18.52–25.62 | 150° | 0.018±0.004 | 0.60 | 0.67 | 0.60 | 234 | 50 |
| $\alpha_4$ | 5.24 | $3^+$ | 18.52–25.62 | 150° | 0.025±0.0055 | 0.70 | 0.63 | 0.70 | 201 | 50 |

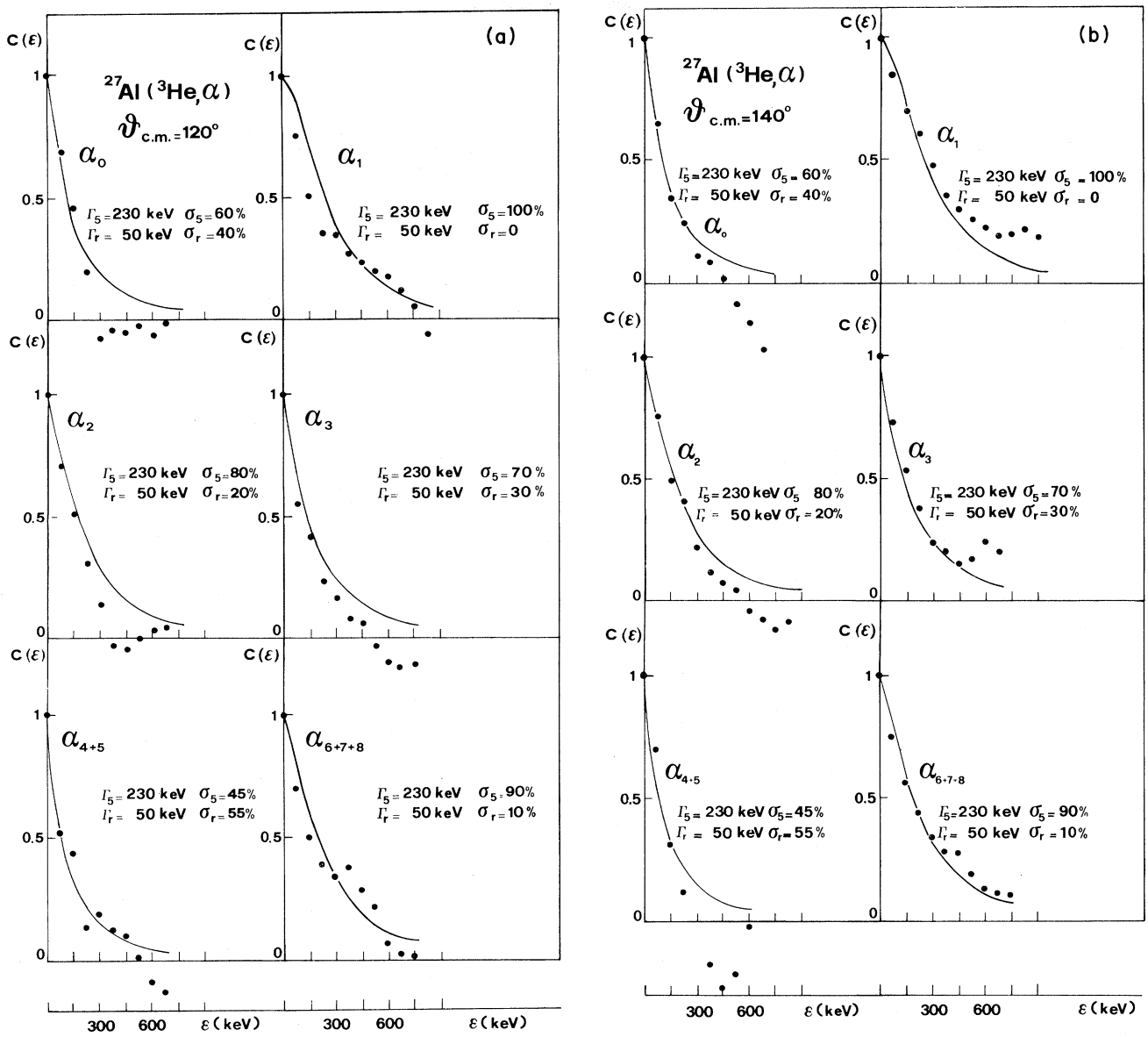


FIG. 9. Same as Fig. 8 for the $^{27}$Al($^{3}$He,$\alpha$) reaction.

the FRD effect,[12] which raises it to about 350 keV. The fact that this value is consistently the same at the two emission angles, 30° and 150°, is very important.

Unfortunately the formula which should be applied in the case of the ground state transition for calculation of the average excitation function (with reduction of the excitons) cannot be used in the $N=3$ stage (see Ref. 5, Eq. 5.17). The statistical calculation is not suitable for this particular transition. In this case we therefore used an empirically constructed average excitation function, chosen by means of the least-square deviation criterion.

In all the other transitions this large $\Gamma$ value does not appear, so we can only deduce that it is not the dominant one. All the average excitation functions and the corresponding autocorrelation functions can be fitted following Ref. 14 with a mixture of emissions from stage 5 (3 for $\alpha_0$) and stage $r$ with practically the same percentages as those given by the spectral density method. The results are shown in Fig. 12 and Table V.

## IV. CONCLUSIONS

It is necessary to make a summary of the results obtained from the measurements and analysis discussed above in order to have a clear understanding of the $\alpha$-emission mechanisms in the reactions being considered.

The first thing to be observed is that the SMCE is the dominating emission mechanism, as was true in the case

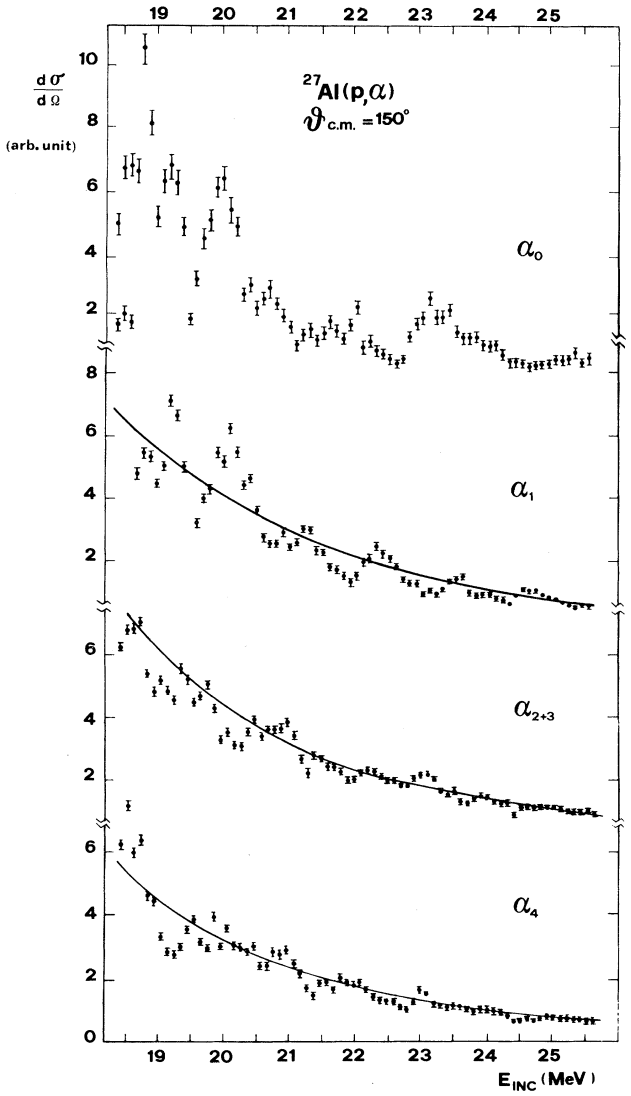


FIG. 10. Excitation functions of four $^{27}$Al(p,$\alpha$) transitions at $\vartheta_{c.m.}=150°$. The curves are the results of the SMCE calculations (see the text).

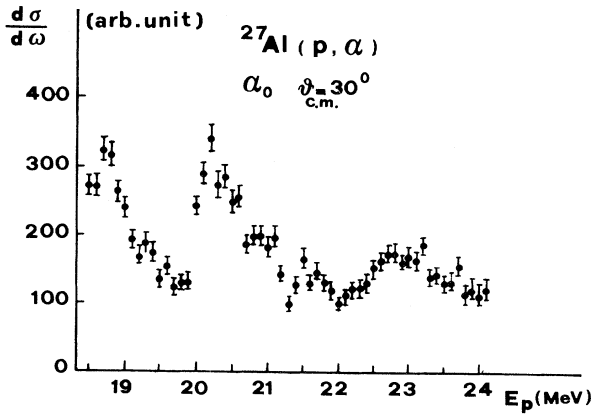


FIG. 11. Excitation function for the $^{27}$Al(p,$\alpha_0$) transition at $\vartheta_{c.m.}=30°$.

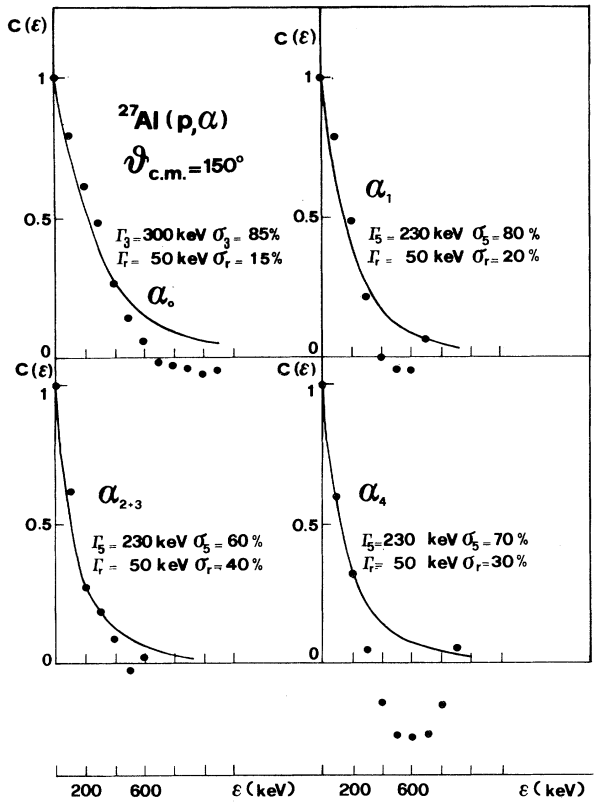


FIG. 12. Same as Fig. 8 for the $^{27}$Al(p,$\alpha$) reaction.

of the proton channels in the similar reactions studied before.[4,6] This is shown by all the reaction characteristics: $\alpha$-spectrum shape, angular distribution shape, average shape of the excitation functions, fluctuation existence, and their correlation widths $\Gamma$. The second interesting result to be pointed out is the emission of alpha particles from the first step of the multistep chain developing in the nucleus. In both types of reactions examined (i.e., reactions initiated by $^3$He and protons) it is clear that the emission must be introduced in the first step in order to explain the average excitation function shape and the fluctuation correlation widths. This important result seems to show the existence of preformed $\alpha$ particles in the target nucleus, although at this stage of the analysis nothing can be quantitatively said about the $\alpha$-preformation probability.

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