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Fluctuations due to statistical multistep compound emission in the $^{25}Mg(^3He, p)$ and $^{25}Mg(^3He, \alpha)$ reactions

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Excitation functions and angular distributions of protons and alpha particles emitted from the $^3He + {}^{25}Mg$ reaction were measured in the ^3He energy range from 8.05 to 20.425 MeV. The excitation functions show large, uncorrelated structures. Analysis on the basis of the autocorrelation function and the spectral density method yields largely varying values of the coherence energy, which can be attributed to the different steps of the statistical multistep compound emission chain. This process explains the average shape of the excitation functions, and also the absolute value of the emitted proton spectrum, measured at 13 MeV incident ^3He beam.

[NUCLEAR REACTIONS ^{25}Mg ($^3He, p$), ($^3He, \alpha$), $E = 8.05 - 20.425$ MeV; measured $\sigma(E; \theta)$; calculated $\sigma(E)$, $\sigma(E_p)$; deduced coherence widths.]

I. INTRODUCTION

Previous work on the ^{27}Al ($^3He, p$) reaction has shown the existence of large fluctuations in the excitation functions of this reaction leading to some of the low-lying excited states of the residual nucleus.[1] More precisely, the characteristic effect pointed out in the above-mentioned paper was the great difference in the coherence width Γ found in the excitation functions corresponding to different final nucleus levels. This effect was interpreted on the basis of statistical multistep compound emission, a new mechanism for nuclear reactions recently proposed by Feshbach, Kerman, and Koonin.[2]

This paper describes new measurements on similar reactions, the $^{25}Mg(^3He, p)$ and $^{25}Mg(^3He, \alpha)$ that were studied in a way very similar to the former but in a much larger incident particle energy range. The excitation functions of the two reactions leading to a number of low-lying excited states were measured for kinetic energy of the ^3He beam ranging from 8.05 to 20.425 MeV. For these measurements two accelerators were utilized: the Legnaro Laboratory's CN Van de Graaff was used in the 8.05–12 MeV range and the Tandem at CEN-DPHNBE in Saclay in the 12–20.425 MeV range. The measurements described herein confirm the effect observed previously and, due to the extended energy range, analysis of the fluctuations includes a much smaller error. In order to obtain all the information necessary to understand the various mechanisms that could be active in these reactions, the angular distribution of the emitted particles was measured at four values of the incident energy (12, 14, 16, 18 MeV) in 15° steps. The complete spectrum of emitted protons was also detected at an energy of 13 MeV.

II. EXPERIMENTAL APPARATUS

The experimental apparatus was essentially the same as that used to measure the ^{27}Al(^{3}He, p) reaction. Only one modification was introduced to make it possible to detect protons and alpha particles at the same time. This was easily done with a telescope of solid state detectors of suitable thickness and with a standard electronic chain. Mass separation was achieved only by the coincidence-anticoincidence method. In the various energy ranges studied, different detectors of suitable thickness were of course used. The emitted particles were detected simultaneously at angles of 30° and 150°, symmetric to 90°.

The two excitation functions were therefore obtained in exactly the same condition of the incident beam. The thickness of the ^{25}Mg target was ~ 200 μg/cm^2 which gave rise to an energy spreading of $\Delta E \sim 20-30$ keV in the incident channel, depending on the incident energy. The overall resolution in the final channel was ~ 200 keV in the 16 -20.425 MeV incident energy range and ~ 100 keV in the 8.05$-$16 MeV range. Figure 1(a) and (b) show an example of proton spectra at both angles.

III. EXPERIMENTAL RESULTS

From the proton and alpha spectra measured in 75 keV energy steps in the entire energy range examined, we obtained the excitation functions for a number of levels, or group of levels, of the two residual nuclei ^{27}Al and ^{24}Mg.

In the 16$-$20.425 MeV energy range, the energy resolution did not allow a clear separation of some levels, which were instead well resolved in the 8.05$-$16 MeV range. Therefore, in the former interval we obtained good excitation functions only for the levels p_0, p_3, and α_0, α_1.

In the 8.05$-$16 MeV range excitation functions were also constructed for levels p_1, p_2, p_4, p_{5+6}, and α_{2+3}, α_4. At 150° the spectra have almost no background [see Fig. 1(b)], at least in the part of interest to us, so calculation of the excitation functions can be done very easily, the error being only statistical. At 30° instead, as shown in Fig. 1(a), the background is often important, thus making the analysis less reliable, since in the majority of these cases the error due to background subtraction was of the same order as the observed fluctuation amplitude.

An example of excitation functions at 30° for the ground state of the two residual nuclei is shown in Figs. 2(a) and (b). All proton and alpha excitation functions obtained at 150° are shown in Figs. 3(a)$-$(f) and 4(a)$-$(d).

IV. ANALYSIS OF THE RESULTS FOR PROTON CHANNELS

The presence of the statistical multistep compound emission mechanism (SMCE) in the ^{25}Mg(^{3}He, p) reaction was pointed out in a previous paper,[3] where almost the complete spectrum of emitted protons was detected and compared with the existing theory of statistical emission mechanisms. It was shown that the best agreement was found when the SMCE formulation was used, even if only in a relative value.

New calculations, developed following the line used in the reaction on ^{27}Al (Ref. 1) analyzed previously, show that good agreement can also be found with prediction of the SMCE in an absolute value. In the present case we have considered the

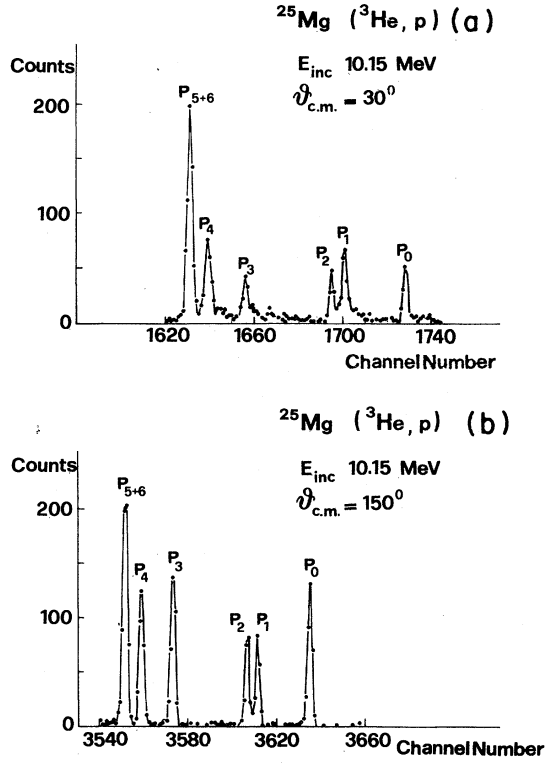

FIG. 1. (a) and (b) Typical proton spectra at 10.15 MeV incident ^{3}He energy.

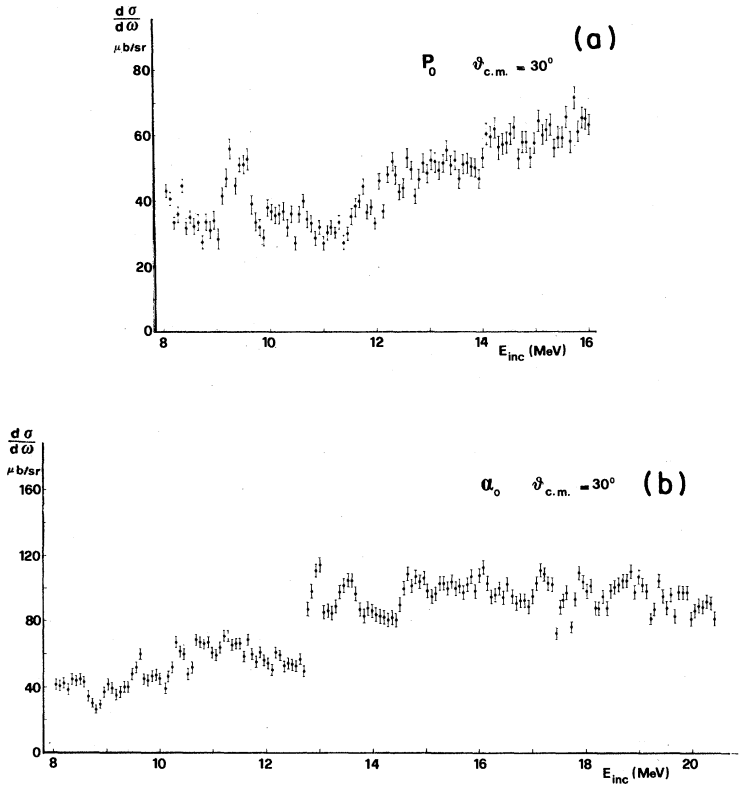

FIG. 2. (a) and (b) Excitation functions at 30° for the ground state of ^{27}Al and ^{24}Mg.

initial exciton number $N_0=5$ (which corresponds to excitation of a particle-hole pair while the ^{3}He is broken into its components).

A critical aspect of the SMCE theory is the definition of a stage in such a way that all the stages following it are included in the so-called "r stage," the last one. The condition required for a certain N stage to be considered "precompound," that is, not included in the "r stage," is as follows[2]:

The level density value ρ_N of the corresponding N exciton state must be at least 10 times smaller than that of the next stage. We therefore truncate the precompound chain when the level density function shows a saturating trend. This means in general that there is no longer much difference between the stages at this point and that a real equilibrium has been reached. In our case, the condition $\rho_{N+2}<10\rho_N$ has already been reached at the stage $N=7$. This stage is therefore included in the r stage. With these assumptions the reaction is seen to proceed through two stages, a "precompound" five-exciton stage and the equilibrium r stage. The results of the calculations in absolute values are compared with the experimental proton spectrum in Fig. 5. In line with these results, the proton emission in channels leading to low-lying excited states of the residual nucleus should be dominated by the multistep compound emission mechanism.

More information on the mechanism active in the proton channels analyzed here can be obtained from the average shape of the excitation functions. These functions were calculated using the MUCOM code, which explicitly computes the SMCE cross section for the case of one final state. The spin of the final channel was approximated to the nearest integer value, disregarding the spin of the outgoing particle. This approximation was in fact made throughout the entire calculation. The cross section of a transition to a separated final state cannot be given as an absolute value because it contains an unkown factor, which represents the amplitude of the wave function corresponding to the particular configuration, i.e., the "exit mode",[2] being considered. In Table I the "spectroscopic factors" are shown as the ratio between the value of σ_{expt} and

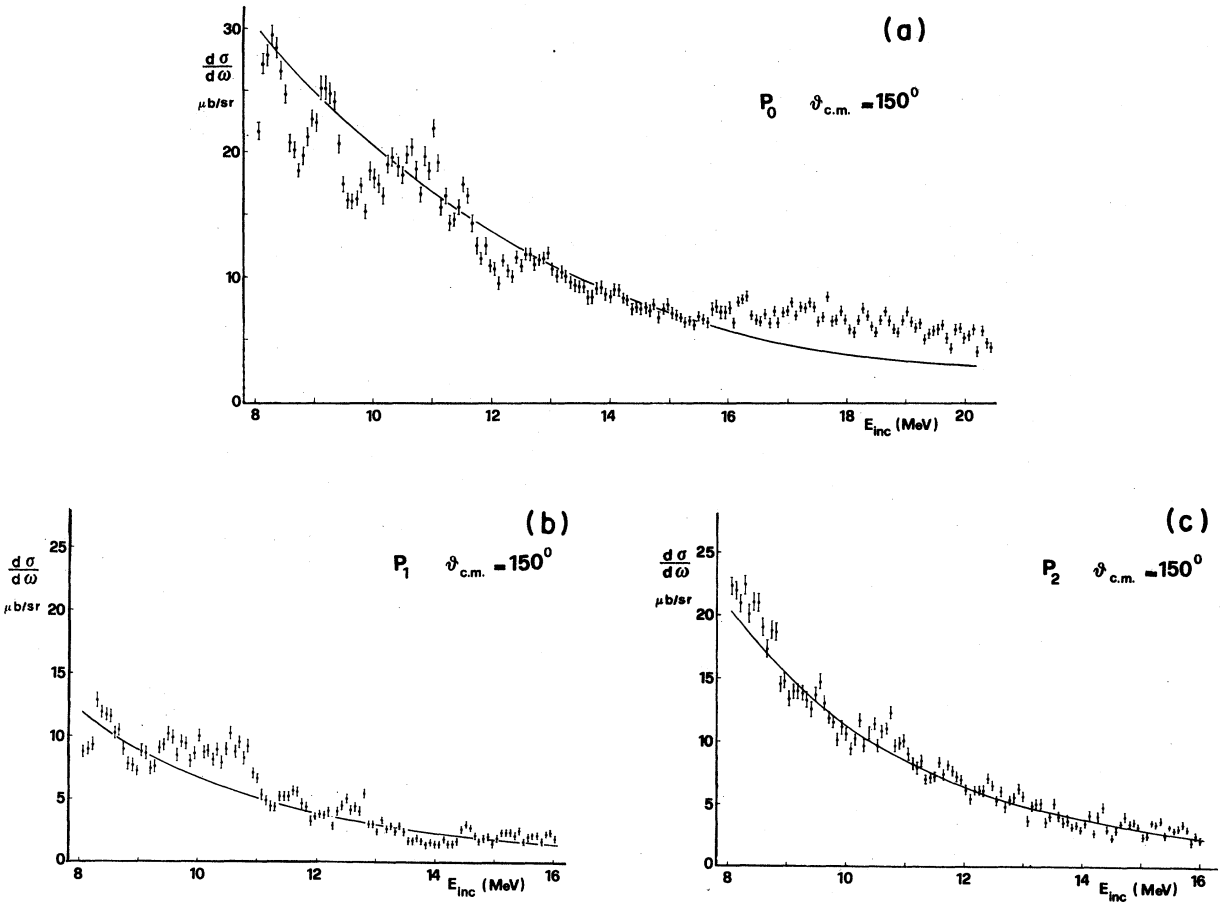

FIG. 3. (a)—(f) Excitation functions at 150° for the measured proton transitions, together with the theoretical calculations (see text).

σ_{theor}.

In Figs. 3(a)—(f), together with the experimental results, the normalized excitation functions that were calculated are shown. In order to fit the average excitation functions correctly, it was always necessary to consider a strong proton emission contribution from the five-exciton stage ($\sim$ 80%) and a much smaller contribution from the r stage ($\sim$20%). In some cases these percentages are different (p_2). Figure 3(d) also shows excitation functions calculated according to the traditional evaporation theory and the pure emission from the five exciton stage and the r stage.

What has been said so far seems to indicate that the reaction being studied is dominated by the SMCE in the transitions leading to the final levels, as is suggested too by the shape of the emitted particle angular distribution. The angular distributions averaged in an incident energy interval of 6 MeV are shown in Figs. 6(a) and 6(b). The asymmetric component, when present, does not seem to make an important contribution to backward emission, being characterized by behavior that is flat or symmetrical to 90°. The transition to the third excited level (p_3) is completely symmetric, thus making the analysis particularly meaningful in this case. A small contribution made by a "direct effect" at 150° is possible in the case of the p_0 level. The obvious presence of direct effect (or multistep direct) at an angle of 30° does not allow profitable comparison of the excitation functions with the average curve calculated on the basis of SMCE. We are therefore concentrating on the results obtained at 150°.

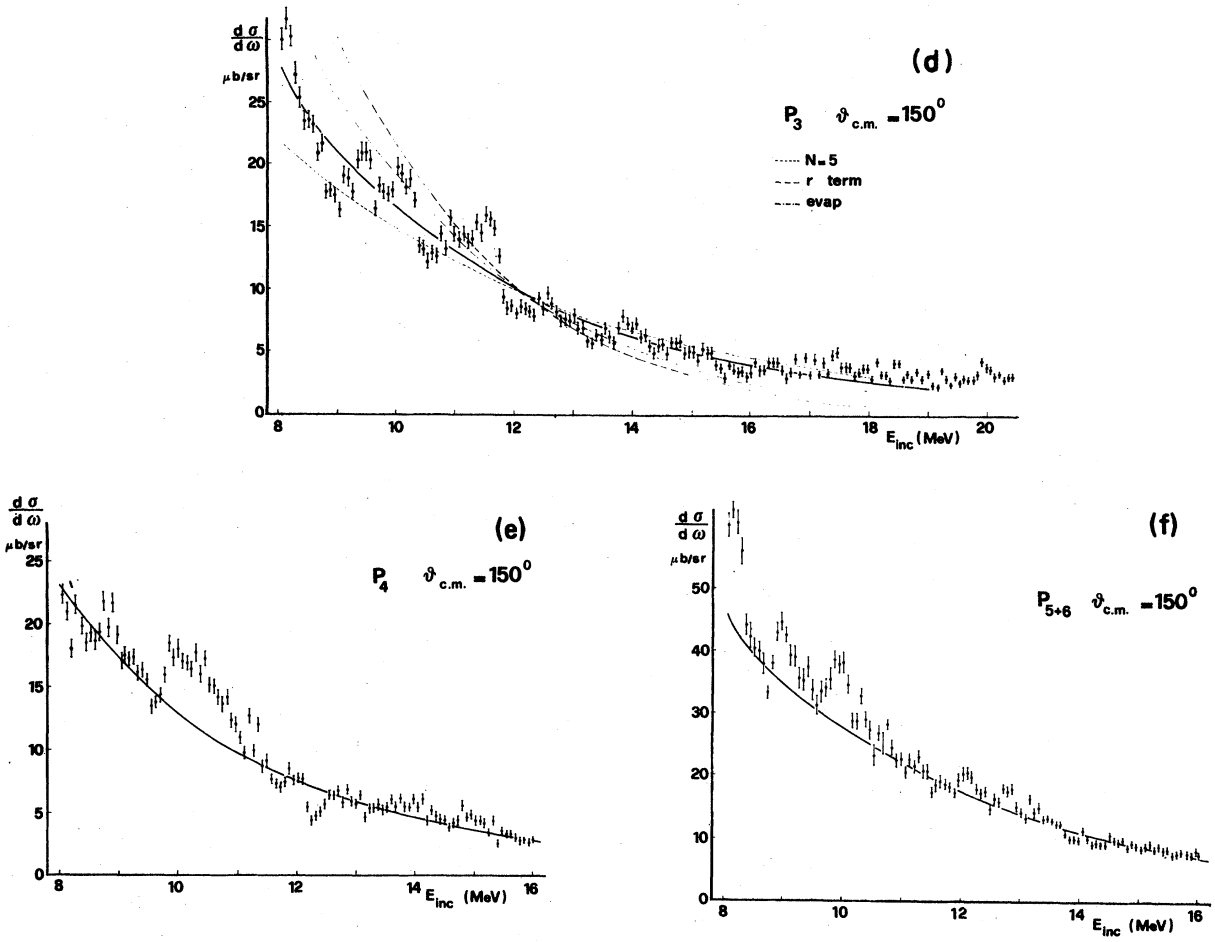

FIG. 3. *(Continued.)*

V. ANALYSIS OF THE FLUCTUATING EXCITATION FUNCTIONS

A particular goal of this study was to obtain precise values for the coherence width Γ of the various final levels, as an improvement on the previous ^{27}Al measurement where the existence of the different widths had already been shown. We therefore carefully examined the experimental excitation functions and chose the parts with characteristics suitable for this analysis. We consequently disregarded those parts of the excitation curves where errors due to statistics or to the proton spectrum background were not really small compared to the unavoidable finite range of data error. Excitation functions with these characterisitcs are generally found in the 8.05—16 MeV range at 150°, where it is possible to extract the Γ value with an error of $\sim$20% or less, due almost entirely to the finite range of the data.

Another important point in the fluctuation analysis is the definition of the average curve. In the present case the average curves to be used as a basis for the fluctuation analysis were obtained by smoothly connecting pieces of straight lines calculated with the minimum square deviation method in energy intervals having a width much larger than that of the fluctuations, i.e., 3 or 4 MeV. The curves obtained in this way are practically the same as the theoretical ones (after normalization, of course).

While precompound emission averaged over final states was studied in detail in the framework of the SMCE mechanism proposed by Feshbach *et al.*,[2] the application of this theory to one isolated final level or to its consequences on the excitation function fluctuation problem has never been examined in detail. The problem of precompound fluctuations for transitions to one level was instead examined by Fiedman, McVoy, Mello, and Hussein[4] in

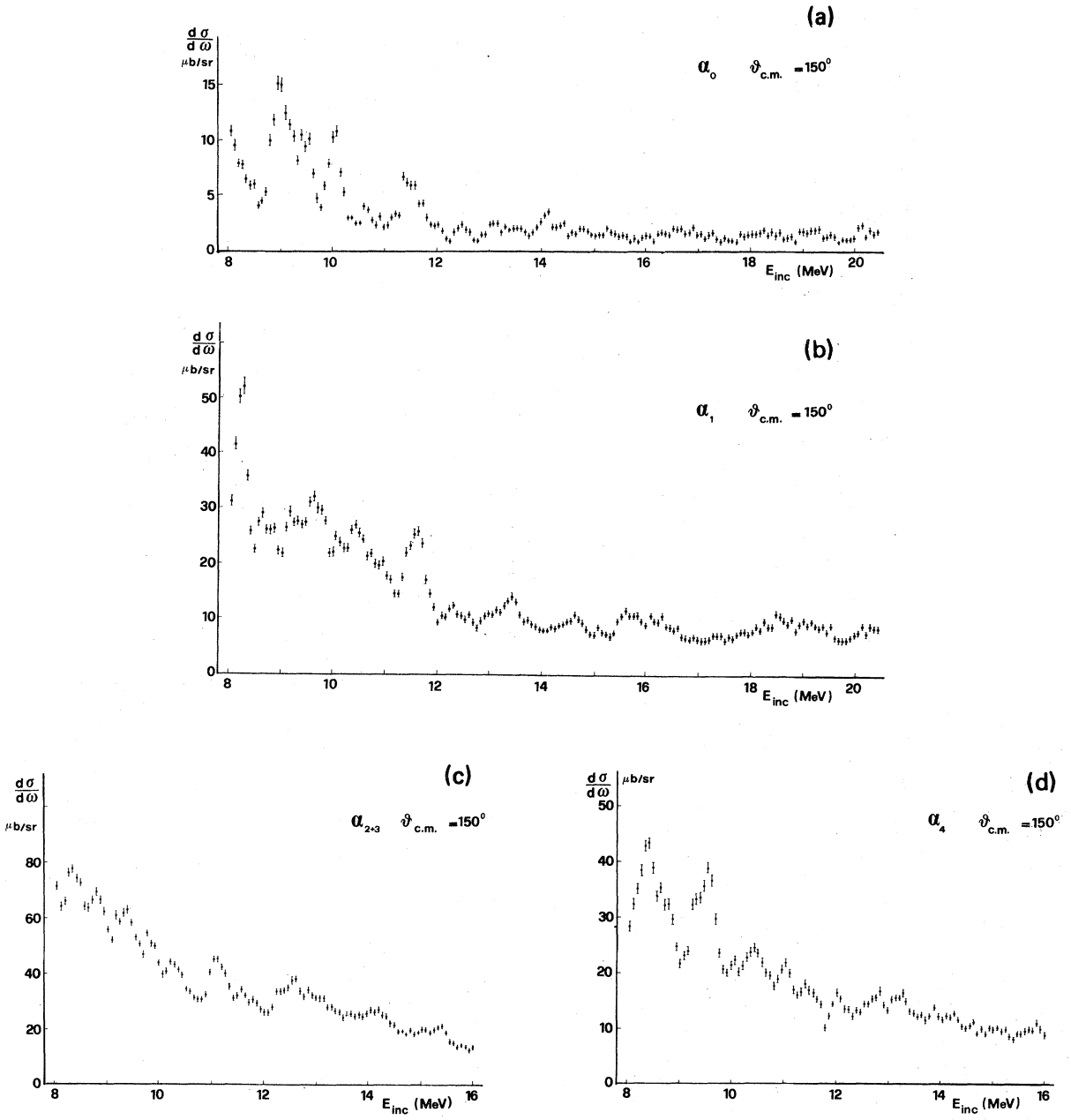

FIG. 4. (a)—(d) Excitation functions at 150° for the measured alpha transitions.

the framework of the "nested doorway model," another formulation of precompound emission with statistical approximation that was proposed recently by some of these authors.[5]

We will, therefore, analyze the fluctuating excitation curves using the results obtained by Friedman *et al.*, on the assumption that the fluctuation effect is a very general one, connected with the hypothesis of equilibrium at each stage of the chain developing inside the nucleus, and therefore, also with possibility of defining a lifetime τ_N for each stage N, related to the coherence width by $\Gamma_N = \hbar/\tau_N$.

Here the fluctuation effect is assumed to be found in the exit channel, in accordance with

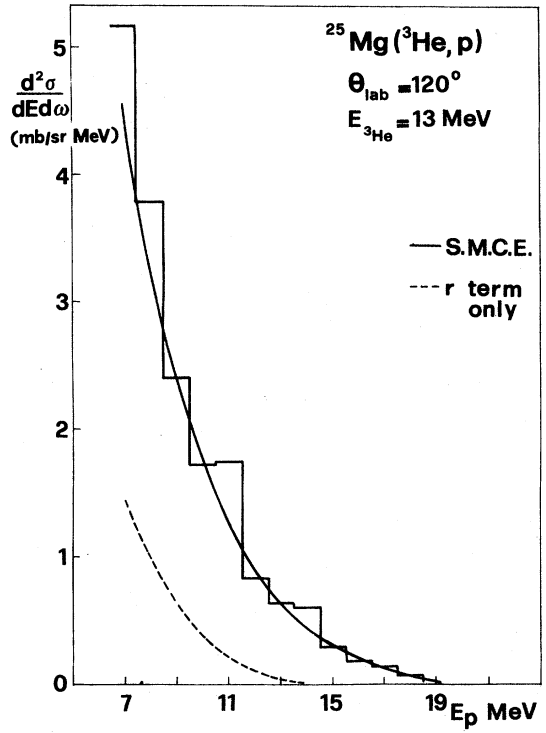

FIG. 5. Experimental spectrum of protons emitted from ^{25}Mg(^{3}He, p) at 13 MeV incident energy and $\theta = 120°$, together with the cross-section calculations done on the basis of the SMCE.

Friedman *et al.*, and its coherence width therefore reveals the stage from which the emitted particle comes. It is assumed that the fluctuation effect connected with the decay from one N-exciton stage to the next $N+2$ stage inside the nucleus is washed out, due to the average over many states. Considering the fluctuating excitation functions that correspond to the separate final states of the

TABLE I. Experimental data and spectroscopic factors ($S = \sigma_{expt}/\sigma_{theor}$) of the measured proton transitions.

Peak	Excitation energy	J^π	S
p_0	0	$\frac{5}{2}^+$	0.41
p_1	0.84	$\frac{1}{2}^+$	0.31
p_2	1.01	$\frac{3}{2}^+$	0.23
p_3	2.21	$\frac{7}{2}^+$	0.35
p_4	2.73	$\frac{5}{2}^+$	0.24
P_{5+6}	2.98–3.00	$\frac{3}{2}^+ - \frac{9}{2}^+$	0.69

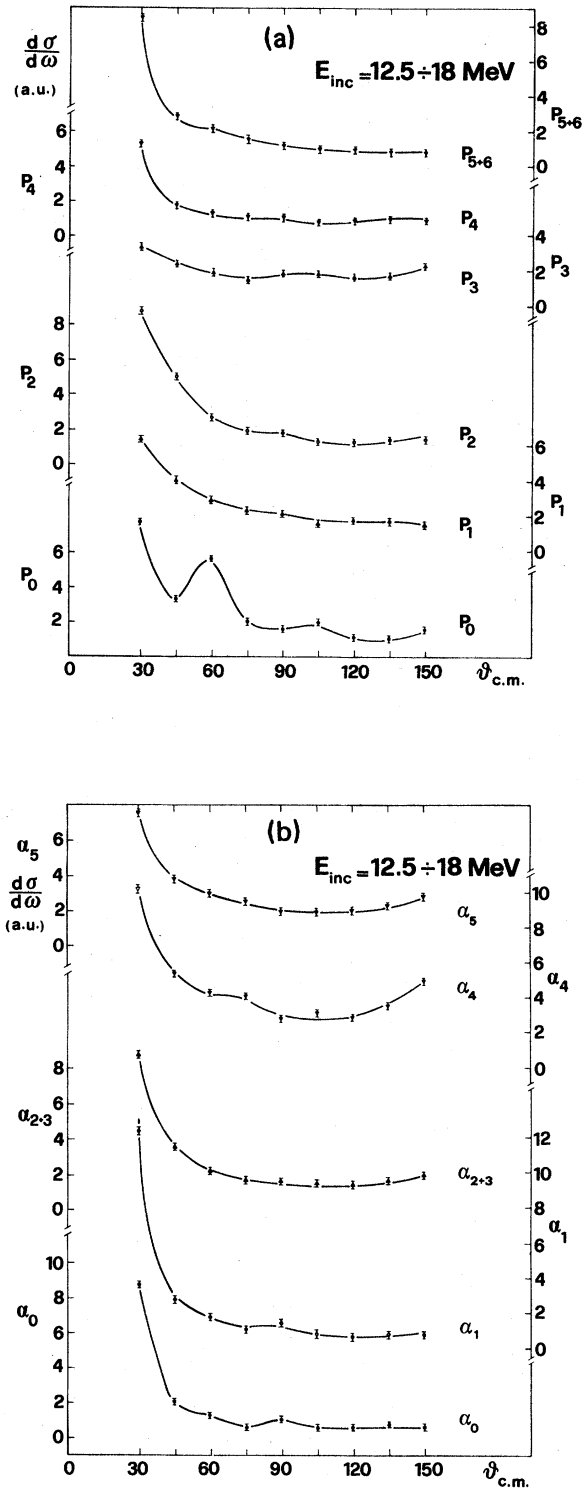

FIG. 6. (a) and (b) Angular distributions of the measured proton and alpha transitions integrated over the incident energy range 12–18 MeV.

residual nucleus studied herein, and following the formulation of the SMCE, we expect to find in each transition a contribution from more than one stage. This is also confirmed by the theoretical excitation functions, which always show a mixture of two contributions. For the interpretation of the experimental results, we decided to use the generalized autocorrelation function developed in Ref. 4, which is derived assuming the presence of more than one coherence width on assumptions which seem to be satisfied in this case, too.

The fluctuating excitation functions have first been analyzed as in the previous paper[1] by means of the classical autocorrelation and cross-correlation function method. Another method recently developed by De Rosa *et al.*,[6,7] the spectral density method, was also applied, and the two methods gave consistent results.

A. Fluctuation analysis with the spectral density method

The spectral density method allows independent determination of both the coherence energies and their relative weights, on the hypothesis that they differ sufficiently among themselves. Even though with this method one could theoretically perform the analysis of the cross sections without having previously determined an average curve to which the fluctuation could be referred, we chose not to do this. In fact, a nonconstant average would give in the spectral density curve a fictitious coherence width. The spectral density can be written as

$$W(\beta_l)=\sum_{i=1}^{f}\pi\frac{A_i\Gamma_i}{\Delta E}\exp\left[-\frac{\Gamma_i}{\Delta E}\beta_l\right], \qquad (1)$$

where $\beta_l=l\pi/m$ where m represents the total number of experimental points and l is an integer between 0 and m, ΔE is the energy step in the excitation functions, Γ_i is the coherence energy for emission from stage i of the precompound chain, and A_i is the weight of the width Γ_i due to the average contribution to the experimental cross section by stage i.

If the Γ_i's are different enough, it is possible to determine a β_{l_0} such that, for $\beta_l>\beta_{l_0}$, a semilogarithmic plot of (1) has straight behavior with slope $-\Gamma_f/\Delta E$, and intercept $\ln[\pi A_f(\Gamma_f/\Delta E)]$ for $\beta_l=0$. With successive subtractions it is then possible to calculate the widths Γ_i and their relative weights A_i. In all the cases considered, the analysis performed with this method has shown the presence of two coherence widths. In Table II the values obtained are reported together with the corresponding relative cross sections. The errors, not explicitly marked, are about 15%, and they are principally due to the finite range of the experimental data and to the indetermination in the de-

TABLE II. Columns 2 and 3 show the Γ values and the relative cross sections obtained with the spectral density method [Eq. (1)]. The result of column 3 should be compared with those of column 4 [obtained with the generalized autocorrelation function, Eq. (2)] and of column 5 (the relative five-excition and r-term cross sections used to fit the average excitation functions).

Peak	Γ (keV)	Relative cross sections (%)		
		Spectral density method	Generalized autocorrelation function	Average excitation function
p_0	30	21	10	10
	245	79	90	90
p_1	48	26	25	25
	270	74	75	75
p_2	58	38	40	40
	209	62	60	60
p_3	40	21	15	20
	240	79	85	80
p_4	30	17	25	25
	197	83	75	75
p_{5+6}	49	21	20	20
	204	79	80	80

finition of the average curve. An example of analysis with the spectral density method for the ^{25}Mg(^{3}He, p)^{27}Al reaction is shown in Fig. 7.

B. Autocorrelation function analysis

Autocorrelation functions have been constructed for all proton excitation functions in the 8.05–16 MeV energy interval. They are shown in Figs. 8(a)–(f). These functions are generally well behaved, showing a tolerable negative undershoot, a usual consequence of the finite range of data error. The coherence width Γ can therefore be easily extracted as the width at half height.

Cross-correlation functions have also been calculated, in order to ensure that there is no significant correlation among the excitation functions corresponding to different final levels, this being a sign of a nonstatistical process. The results of these calculations are given in Table III showing the Γ values. Also given for each case are the values of $C(0)$, the mean square deviation, and the values of $C_{ij}(0)$, the cross-mean square deviation coefficient.

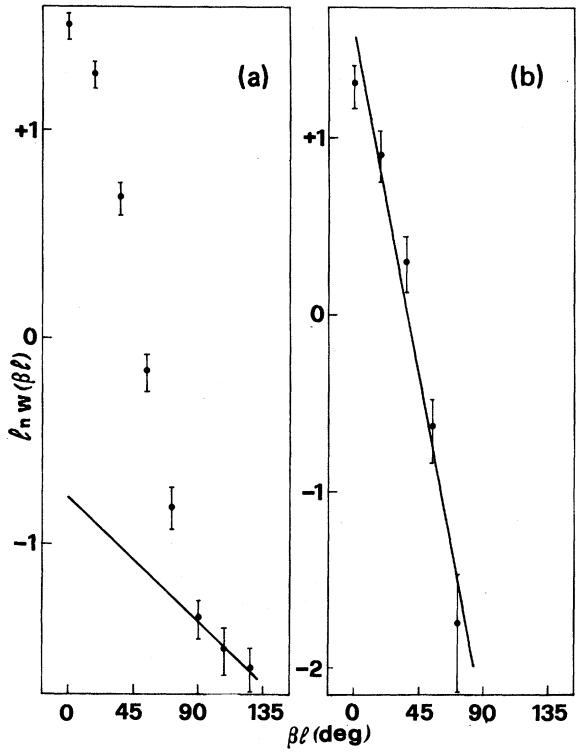

FIG. 7. (a) Spectral density analysis of the ^{25}Mg(^{3}He,p_4) reaction at 150°. The straight line fitting the last part of the curve corresponds to $\Gamma_2 \simeq 30$ keV. (b) The same, after subtraction of the term $\pi(A_2/\Delta E)\Gamma_2 \exp[-(\Gamma_2/\Delta E)\beta_l]$. The straight line shown corresponds to $\Gamma_1 = 197$ keV.

V. COMMENTS ON THE RESULTS FOR PROTON CHANNELS

Table III in a number of cases shows mainly large Γ values between 150 and 200 keV. Only one case (p_2) has a much smaller value, 70 keV. It is very interesting to observe that the only theoretical average curve that needs a strong contribution from the r stage is the very one with the small Γ value belonging to the p_2 level transition. Following the results of the spectral density method, which indicated the simultaneous presence of two Γ values in each proton channel, all the autocorrelation functions have been subsequently analyzed in terms of two Γ values, using the generalized autocorrelation function developed by Friedman *et al.*[4] and applied recently to the similar results obtained for the ^{27}Al(^{3}He, p) reaction.[8]

This function in the absence of direct effect reads as follows:

$$C(\epsilon) = \left| \sum_N \langle \sigma_n^{\mathrm{fl}} \rangle \frac{\Gamma_N}{\Gamma_N + i\epsilon} \right|^2 , \tag{2}$$

where $\langle \sigma_N^{\mathrm{fl}} \rangle$ is the average value of the fluctuating cross section connected with the N-exciton stage, which has a width Γ_N. In our case the summation in Eq. (2) is limited to two terms, which on the basis of the theoretical calculations reported in Sec. IV are attributed to the five-exciton stage and to the final stage (r term). The results of this analysis are shown in Figs. 8(a)–(f). All the autocorrelation functions can be well reproduced by assuming the presence of two coherence widths, $\Gamma_5 \simeq 220$ keV and $\Gamma_r \simeq 50$ keV (roughly the average values of the sets of the "small" and the "large" values determined by means of the spectral density method). Moreover, it turns out that the two fluctuating cross sections have practically the same percentages as those needed to fit the average excitation functions and as those extracted by the spectral density method (see Table II).

Inspection of the C_{ij} quantities (the cross-mean-square-deviation coefficients) shows generally small values, in accordance with the hypothesis of statistically uncorrelated structures. The same situation is found upon examination of the excitation

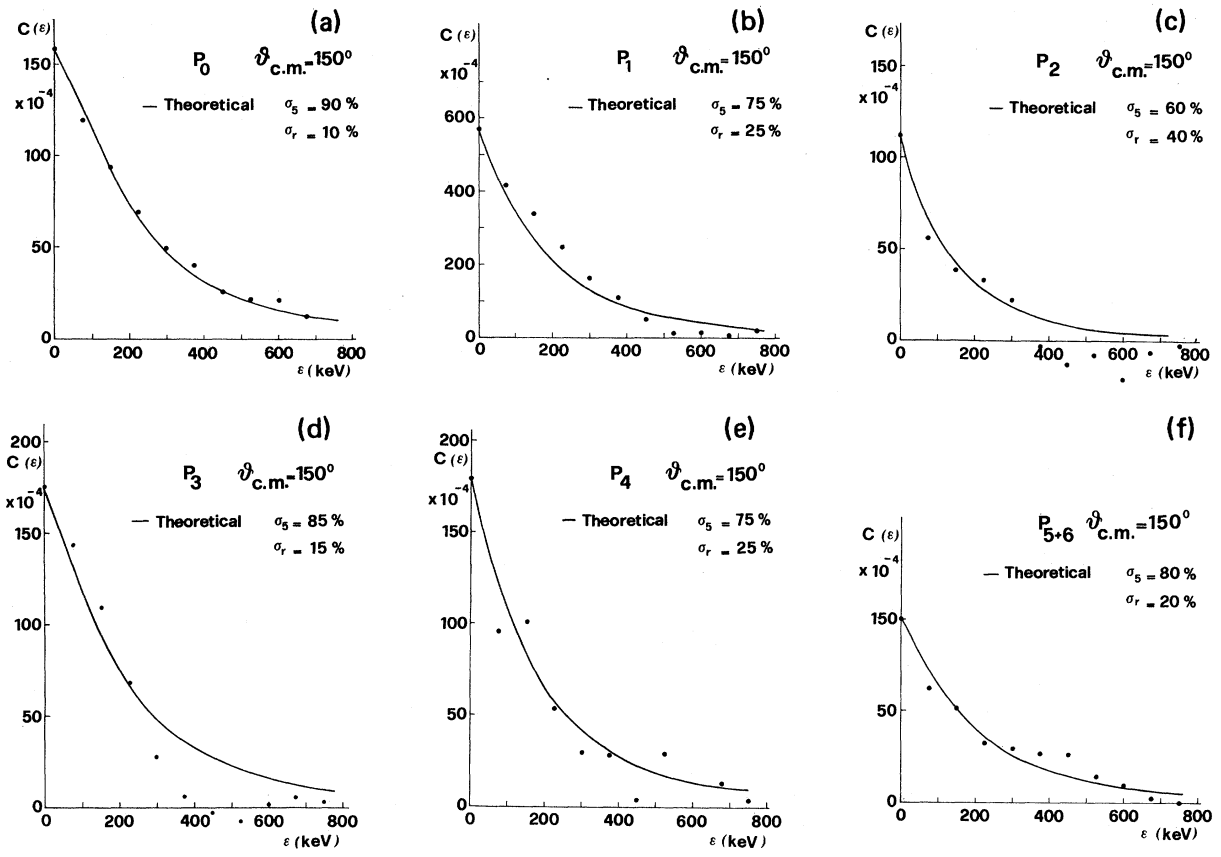

FIG. 8. (a)—(f) Autocorrelation function analysis of the measured proton transitions (points) together with the theoretical shapes calculated by means of Eq. (2) with $\Gamma_5=220$ keV, $\Gamma_r=50$ keV. The relative cross sections obtained from the best fit are indicated in each case.

functions corresponding to the same level but to different angles (30° and 150°), as can be seen by comparing, for example Figs. 2(a) and (b) with Figs. 3(a) and 4(a).

The information contained in $C(0)$ (the mean square deviation coefficeint) cannot by properly used now due to the absence of an appropriate theoretical calculation for emission due to a mul-

TABLE III. Column 2 shows the Γ values for proton channels at $\theta=150°$, obtained by means of the autocorrelation function method, in the 8.05—16 MeV indcident energy range. The same values are shown in column 3 after correction for the finite range of data effect. Columns 4 and 5 show the mean square deviation coefficients and some typical cross mean square deviation coefficients.

Peak	$\Gamma_{\text{expt}}\pm\Delta\Gamma$ (keV)	$\Gamma_{\text{expt. corr.}}\pm\Delta\Gamma$ (keV)	$C(0)\pm\Delta C(0)$	$C_{ij}(0)$
p_0	180±40	190±43	0.0158±0.004	
p_1	185±42	200±45	0. 057±0.015	0.0053
p_2	70±10	70±10	0.0191±0.002	0.0019
p_3	180±40	190±43	0.0174±0.004	0.0052
p_4	175±40	185±43	0. 018±0.004	0.0021
p_{5+6}	155±33	165±36	0. 010±0.002	0.0011

TABLE IV. Column 5 shows the Γ values for α channels at $\theta=150°$, obtained by means of the autocorrelation function method. The same values are shown in column 6 after correction for the finite range of data effect. Column 7 shows the mean square deviation coefficients.

Peak	Excitation energy (MeV)	J^π	Incident energy range analyzed (MeV)	$\Gamma_{\text{expt.}}\pm\Delta\Gamma$ (keV)	$\Gamma_{\text{expt. corr.}}\pm\Delta\Gamma$ (keV)	$C(0)\pm\Delta C(0)$
α_0	0	0^+	12–20.425	100±17	105± 17	0.07±0.014
α_1	1.37	2^+	8.05–12	120±31	130± 34	0.043±0.013
			12–16	175±55	200± 70	0.024±0.009
			16–20.425	250±91	295±117	0.025±0.01
			8.05±20.425	250±66	270± 75	0.027±0.007
α_{2+3}	4.12–4.24	4^+-2^+	8–16	165±36	175± 39	0.013±0.003
α_4	5.24	3^+	8–16	120±22	125± 22	0.017±0.003

tistep mechanism. It can be seen that the variation with the final level spin of this coefficient agrees with the usual rule, that is the lowest spin corresponds to the biggest fluctuation amplitude.

VII. ALPHA-CHANNEL ANALYSIS

The fluctuations with the largest amplitude (transition to ground state of ^{24}Mg), certainly connected with the channel zero spin, are found in the excitation functions of the alpha-channels [see Figs. 4(a)–(d)]. There is also one case (α_1) where the analysis, due to good experimental conditions, can be done in the complete incident energy interval examined, that is 8.05–20.425 MeV, allowing observation of the Γ variation with the energy.

Analysis of the fluctuations found in the α channels shows Γ values very similar to those found in the case of protons. Table IV shows that here the minimum value found is $\sim$100 keV and the maximum $\sim$300 keV, in the highest energy part of the α_1 channel. For the alpha channels we are limiting ourselves to pointing out the existence of the same effect as found in the proton channels. The impossibility of calculating good average excitation functions due to lack of knowledge of the α emission, particularly in the case of emission from the first stage, would create uncertainty in the interpretation of the Γ values. This analysis will be done in the future.

VIII. CALCULATION OF THE ABSOLUTE VALUE OF THE COHERENCE WIDTH

Following the SMCE formulation and introducing the improvements described in (Ref. 9) concerning the use of realistic bound and unbound wave functions and level density values, we calculated the coherence widths in absolute values. In order to reproduce the experimental value of about 220 keV for Γ_5, we set the value of the zero-range two-body residual interaction strength at about 3 MeV. This value was the same as the one already determined for ^{27}Al(^{3}He, p), thus still being of the correct order of magnitude but smaller than what is usually used with this kind of microscopic interaction.[10]

We believe that this difference is due to the fact that many bound wave functions have been calculated in an excitation energy range between the Fermi energy and the binding energy. This range is usually unexploited by the usual calculations of the nuclear reaction matrix elements.

IX. CONCLUSIONS

The results found in the case of the reactions analyzed here are very similar to the ones described in the previous work on ^{27}Al(^{3}He, p). Different Γ values are found for different final levels, ranging from a minimum value of $\sim$70 keV to a maximum of $\sim$200 keV for the proton channels and from $\sim$100 to $\sim$300 for the alpha ones. Such a large variation cannot be attributed to the different spin values of the final level involved. Calculations done on this point show a maximum variation of $\sim$10%.

In some recent papers the variation in the Γ values in the fluctuating excitation functions of various exit channels was attributed to the different isospin values of the final level involved.[11]

This explanation is excluded in our case because all the alpha channels studied here have the same isospin, $T=0$, while all the proton channels have an isospin of $T=\frac{1}{2}$.

As in the case of the ^{27}Al(^{3}He, p) reaction, we attribute the large variation in the Γ values of the various exit channels to the presence of particles emitted through the different steps of the SMCE mechanism. This conclusion is confirmed by the agreement between the experimental and calculated excitation functions. The results described in this paper together with those obtained for ^{27}Al(^{3}He, p) confirm the importance of the statistical multistep compound mechanism in the reaction induced by ^{3}He. This fact is due to the relatively high value of the compound nucleus excitation energy in comparison to the relatively low value of the incident energy, which causes a negliglible direct effect contribution. Moreover, the starting point of the multistep compound chain corresponds in these ^{3}He induced reactions to five excitons, as shown by the spectrum shape. This fact gives rise to coherence widths having just the "right value" to be easily recognized in a fluctuating excitation function.

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