Statistical multistep compound emission in the $^{27}Al(^3He,p)^{29}Si$ reaction

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Excitation functions and angular distributions of protons emitted from the reaction $^{27}Al(^3He,p)^{28}Si$ have been measured in the energy range from 9 to 14 MeV. Some of the excitation functions show the presence of fluctuations that can be attributed to the statistical multistep compound emission. This effect explains also the shape and absolute value of the emitted proton spectrum measured at 13 MeV incident ^3He beam. This comparison yields the value of the strength of the residual two-body interaction.

[NUCLEAR REACTIONS $^{27}Al(^3He,p)^{28}Si$, $E=9$–14 MeV: measured $\sigma(E)$, $\sigma(E, Ep)$, $\sigma(Ep,\theta)$. Deduced coherence energy Γ. Calculated residual two-body interaction strength.]

I. INTRODUCTION

The problem of precompound emission has received considerable attention during the last few years, starting with the proposal of this emission mechanism by Griffin[1] in 1966. Since then many models have been developed, the most widely used being the exciton model, the hybrid model, the geometry dependent hybrid model, and the formulations using a master-equation solution.[2] All of them have enjoyed much popularity due to their success in representing a large number of experimental results.

It is clear that these models have helped provide insight into this problem but it must also be recognized that all these calculations are more or less classical and are therefore far from representing an ultimate answer to the precompound problem. Indeed, one limitation of this kind of calculation is the inability to describe the angular distribution of emitted particles.

A quantum-mechanical approach to precompound problems was given later by Mantzouranis *et al.*[3] but with only limited success in representing experimental angular distributions. More recently, Feshbach *et al.*[4–6] proposed the existence of two different kinds of precompound emission, both developed on the basis of quantum mechanics. The first is called "statistical multistep compound emission" and predicts angular distributions symmetric to 90°. The second, "statistical multistep direct emission," predicts forward peaked angular distributions.

Upon consideration of this situation in the description of precompound emission, it becomes evident how important it is to provide new kinds of experimental results in order to check more accurately the validity of the theories proposed so far.

II. THEORETICAL MOTIVATION FOR THE EXPERIMENTS

We started with the observation that in some precompound emission theories, namely the exciton model and the statistical multistep compound theory, a fundamental quantity is defined, $\Gamma_n^{\downarrow}$, the damping width, which is the width of the state containing n excitons (particles and holes) for transition to the next more complex state with $n+2$ excitons. Adding the width for emission into the continuum from the same state, $\Gamma_n^{\uparrow}$, to the $\Gamma_n^{\downarrow}$, a quantity is obtained that is directly related to the mean life τ_n of the n-exciton state:

$$\Gamma_n = \Gamma_n^{\downarrow} + \Gamma_n^{\uparrow}, \quad \tau_n = \frac{\hbar}{\Gamma_n}.$$

The reaction is then seen as the sum of noninterfering contributions from different sets of quasistationary states with different exciton numbers formed in the composite nucleus (target plus incident particle).

When the average distance D_n of these states is smaller than the corresponding Γ_n, there is complete mixing among the states having the same number of excitons, so a situation is obtained in which many states are excited at the same time and therefore interfere with each other. In such a situation we expect the production of fluctuations in

the excitation functions of a reaction which leads to separate final levels of the residual nucleus. This effect can be considered a generalization of the Ericson fluctuations, which were related to emission from the last stage of the equilibration chain, corresponding to compound nucleus formation.[7]

In the same way that the coherence energy gives the width of the compound states in the Ericson fluctuation effect, the width of first stage states is given directly by the "coherence energy" of fluctuations found in an excitation function of a reaction where the emitted particles come from the first stage of the chain of precompound states. The existence of this kind of fluctuation connected with "doorway states" was suggested by Feshbach *et al.* before the formal treatment of precompound emission.[8]

The experiment described in this paper was set up in order to look for fluctuations in precompound emission. We studied different aspects of the $^{27}Al(^{3}He,p)^{29}Si$ reaction at an incident ^{3}He beam energy ranging from 9 to 14 MeV, such as emitted proton spectrum shape, angular distributions, and excitation functions corresponding to separate final levels. The corresponding excitation energy in the composite nucleus ^{30}P ranges from ~25 to ~30 MeV. On the basis of Ericson's formulas for multiexciton level densities it is very easy to show that the distance D of the level formed in the first stage of the reaction is very much smaller than all the Γ we obtain from our measurements. Therefore, the conditions for the existence of fluctuation are met here.

III. EXPERIMENTAL APPARATUS

The $^{3}He^{2+}$ beam produced by the Legnaro Laboratory Van de Graaff accelerator was focused on a ^{27}Al target that was ~200 $\mu g/cm^2$ thick. The emitted protons were detected by means of two Si detectors 5 mm thick set at angles of 60° and 150°. The energy loss of the ^{3}He beam in the target was about 15 keV. An absorber 18 mg/cm^2 thick was placed in front of both detectors in order to absorb the α particles emitted in the $(^{3}He,\alpha)$ reaction.

Proton peaks corresponding to 13 low lying levels of the residual nucleus ^{29}Si were easily detected in the proton spectrum, which was measured at both angles simultaneously. These spectra, recorded every 50 keV from 9 to 14 MeV incident ^{3}He kinetic energy, allow the construction of excitation functions corresponding to each resolved level of the ^{29}Si nucleus.

Due to the higher background of the 60° spectra and larger error in the peak fitting procedure, only two excitation functions were constructed at this angle.

Another measurement was performed in order to obtain the angular distribution of the proton peaks. The shape of the emitted proton angular distribution is a truly important test for distinction among the different emission mechanisms. The proton spectrum was detected at nine angles from 30° to 150° at intervals of 15° and for six values of the incident ^{3}He energy, from 8 to 13 MeV.

In a third measurement the proton spectrum was measured from a low cutoff of 13 MeV up to the high energy end of the protons. The ^{3}He beam

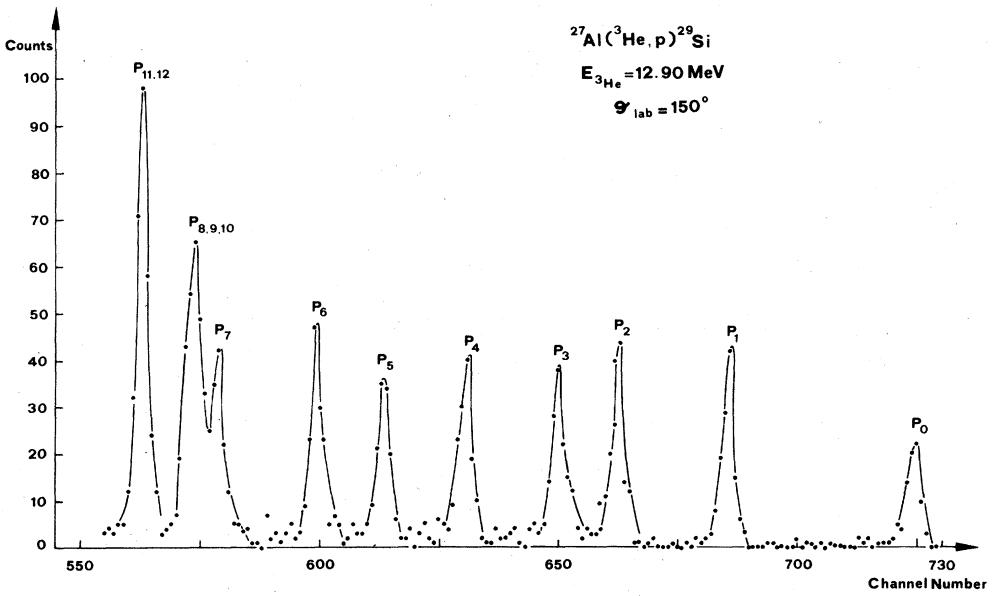


FIG. 1. A typical proton spectrum taken at 12.9 MeV incident ^{3}He energy and ϑ_{lab}=150°.

of this measurement had an energy of 13 MeV. This measurement was meant to be used for comparing the spectrum averaged over the final levels with existing theories. For this measurement, a telescope of two silicon detectors was used, and protons were detected by means of the standard mass identification technique.

IV. DESCRIPTION OF EXPERIMENTAL RESULTS

A. The angular distributions

A typical proton spectrum is shown in Fig. 1. Curves giving the angular distributions of proton peaks corresponding to incident ^{3}He energies of 8, 10, and 12 MeV are shown in Figs. 2(a)–2(c). Figure 2(d) shows the angular distributions integrated over the energy range 10–13 MeV. These angular distributions show that the structures they exhibit at angles larger than 60° cannot be due to a direct effect. Indeed, these structures change very much with energy, decreasing in amplitude and being completely washed out after averaging over an energy interval of 3 MeV. The forward peaking restricted to angles <60° is on the contrary connected with a contribution from a direct effect that we will not discuss here. A distorted-wave Born approximation (DWBA) calculation of the angular distributions of protons from the same reaction at similar energies has been done by H. Nann *et al.*[9] Their analysis shows that it is not possible to fit the shape of the angular distributions at angles >60° by means of a direct effect.

The structures in the angular distributions can be explained by the existence of interference in the entrance channel, the same effect that gives rise to fluctuations in the excitation functions. It is therefore possible to conclude that the most important contribution to the proton emission comes from a mechanism having an angular distribution symmetric about 90°, and that a contribution from a direct effect to the backward part of the emission can be disregarded.

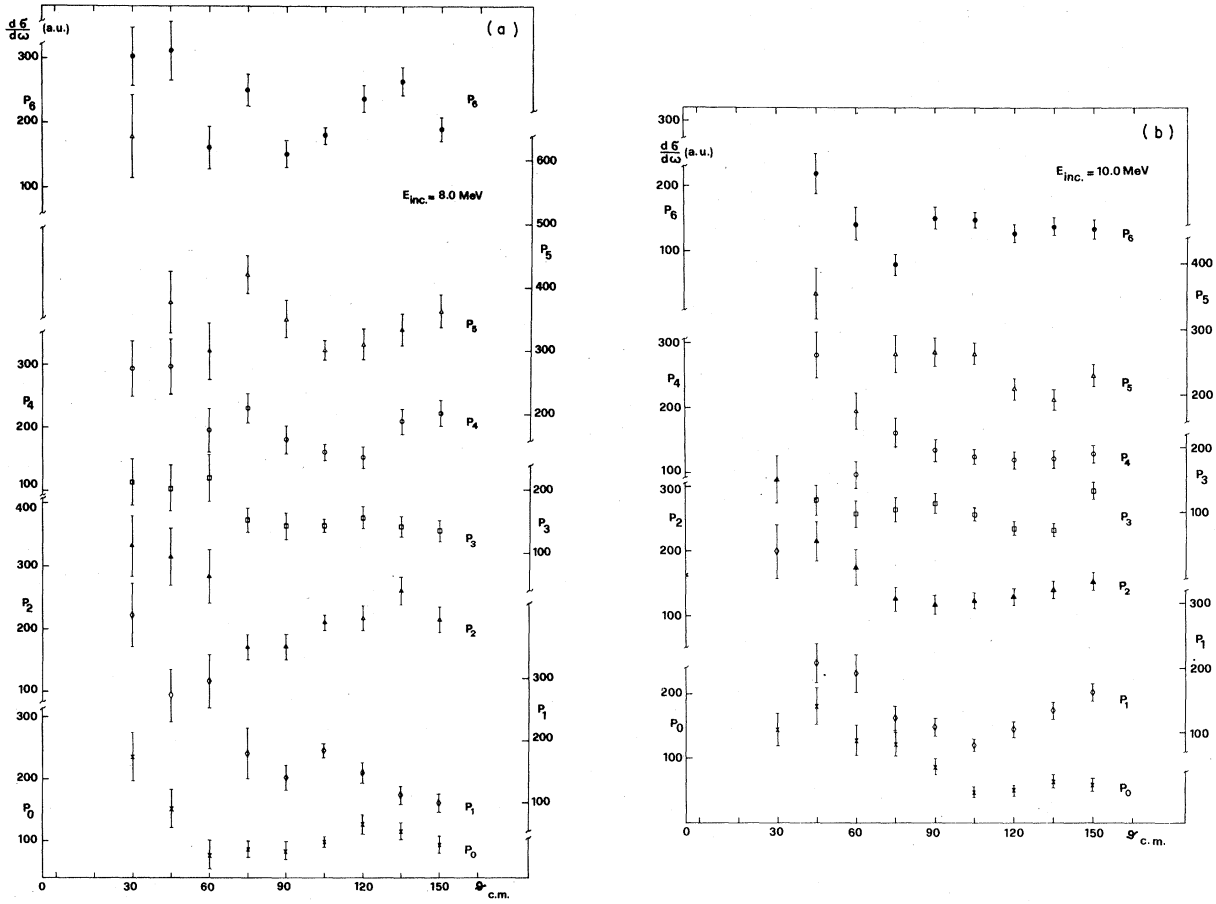


FIG. 2. (a)–(d) Angular distributions of protons corresponding to seven final levels of ^{29}Si at ^{3}He energies of 8, 10, and 12 MeV and the same (d) integrated over the energy range 10–13 MeV.

B. The excitation functions

The excitation functions obtained as described above are shown in Figs. 3(a)–3(j). All of them show the presence of fluctuations. Indeed, by comparing the different curves by means of a cross-correlation function it can be seen that no correlation is found among curves corresponding to different final levels, or to different angles and the same final levels. This excludes the possibility that the peaks appearing in the excitation functions are due to resonances in the entrance channel. Moreover, the excitation functions measured at 150° show more pronounced fluctuations than those found at 60°. This is also in agreement with the fluctuation theory, as the number of independently fluctuating channels becomes smaller as the emission angle approaches 0° or 180°.

These excitation functions must be analyzed in order to extract the "correlation width." In the experimental conditions of the measurements being discussed here, that is, with energy resolution of the incident beam smaller than the "coherence width" Γ, the best method for extracting the value of Γ is the one based on the construction of an "autocorrelation function."[10] This method was used to analyze the curves shown in Figs. 3(a)–3(j). Similar results were obtained by means of an analysis method developed by some of the authors of the present paper.[12] The maxima counting method also gives similar results. An important point in calculating an autocorrelation function is determination of the "average curve." What generally happens in measurements of nuclear reaction excitation functions is that the average curve changes with the energy on an energy scale not much greater than the fluctuation coherence energy, so that determination of the average curve from the experimental points may be quite a problem. In the present case, we have chosen for measurement an energy range corresponding to a smooth variation of the average curve, that is, beginning after the bump due to the Coulomb barrier effect. To obtain the average curve for the excitation functions, the total energy range was divided into three partly overlapping levels. For each of them a straight line was drawn with the least square method, after which the final curve was obtained by just smoothly

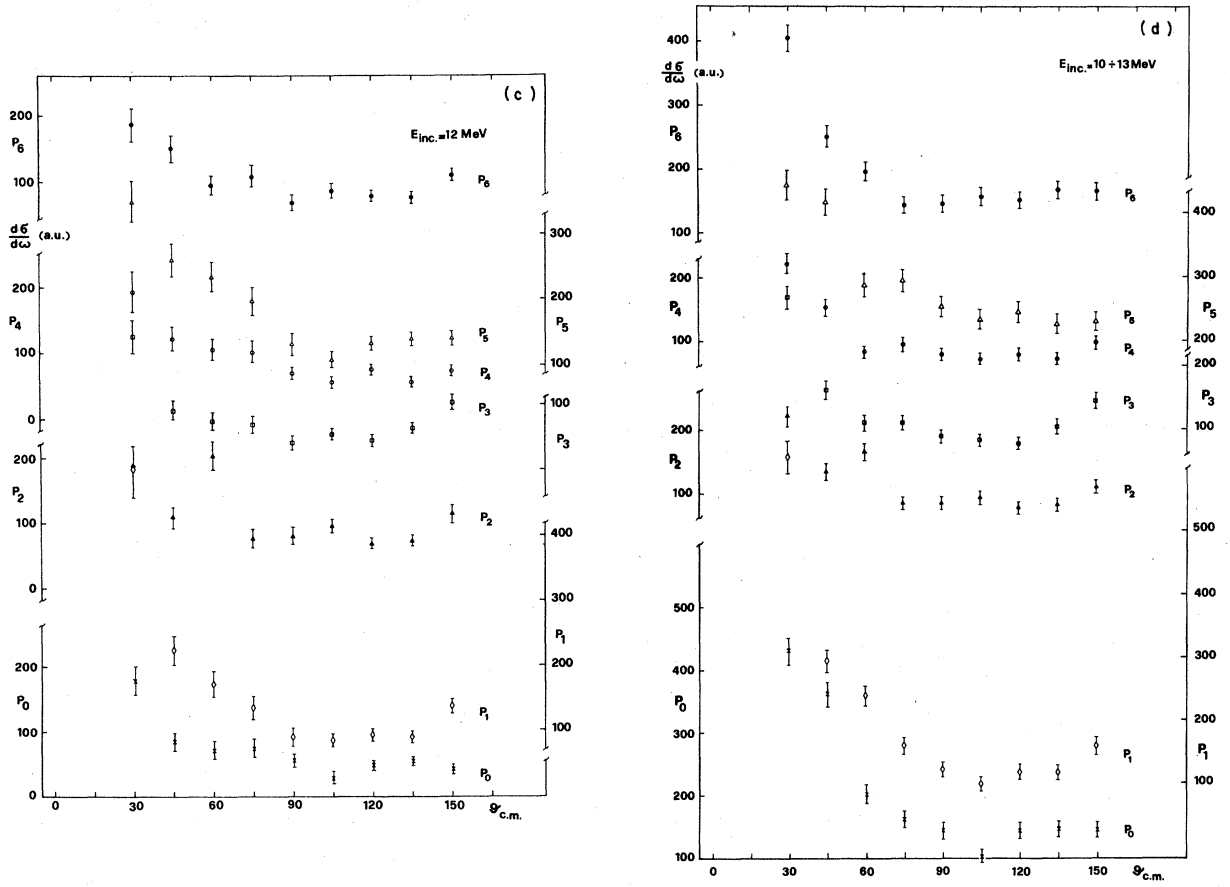


FIG. 2. *(Continued).*

TABLE I. Γ values and relative intensities of measured transitions.

Peak	Exc. energy (MeV)	J^π	$\Gamma^{60°}_{\text{expt.}}$ (keV)	$\Gamma^{60°}_{\text{expt. Corr.}}$ (keV)	$\Gamma^{150°}_{\text{expt.}}$ (keV)	$\Gamma^{150°}_{\text{expt. Corr.}}$ (keV)	$2J+1$	σ (a.u.)
p_0	0	$\frac{1}{2}^+$			50	55	2	4
p_1	1.27	$\frac{3}{2}^+$	50	55	150	165	4	6.5
p_2	2.03	$\frac{5}{2}^+$			50	55	6	7.7
p_3	2.43	$\frac{3}{2}^+$			100	105	4	5.3
p_4	3.07	$\frac{5}{2}^+$			70, 200	75, 230	6	6.5
p_5	3.62	$\frac{7}{2}^-$	(50), 200	(55), 230	200	230	8	12.5
p_6	4.08	$\frac{7}{2}^+$			70	75	8	8
p_{11+12}	5.25, 5.29	$\frac{9}{2}^-, \frac{7}{2}^+$			100	105		

connecting each of the three straight lines with the others. Two of the average curves obtained in this way are shown as examples in Figs. 3(b) and 3(i). Other methods of calculating the average curves have been used with the same results.

Some examples of the autocorrelation functions obtained from the experimental excitation functions are shown in Figs. 4(a)–4(d). Owing to the rather large range of data analyzed, they are of good quality, so that the coherence energy can be extracted with a relatively small error. The Γ values thus obtained must, however, be corrected for the well-known finite energy range of data (FRD) error.[11]

The final values of Γ are given in Table I. The most striking feature that columns 5 and 7 show is the variety of Γ values obtained, ranging from 230 keV for level p_5 to 55 keV for levels p_0 and p_2. This large difference is well out of errors. In one instance (p_1) different Γ values are found for transition to the same level but at different angles. In other instance (p_4, p_5) it looks as though two differ-

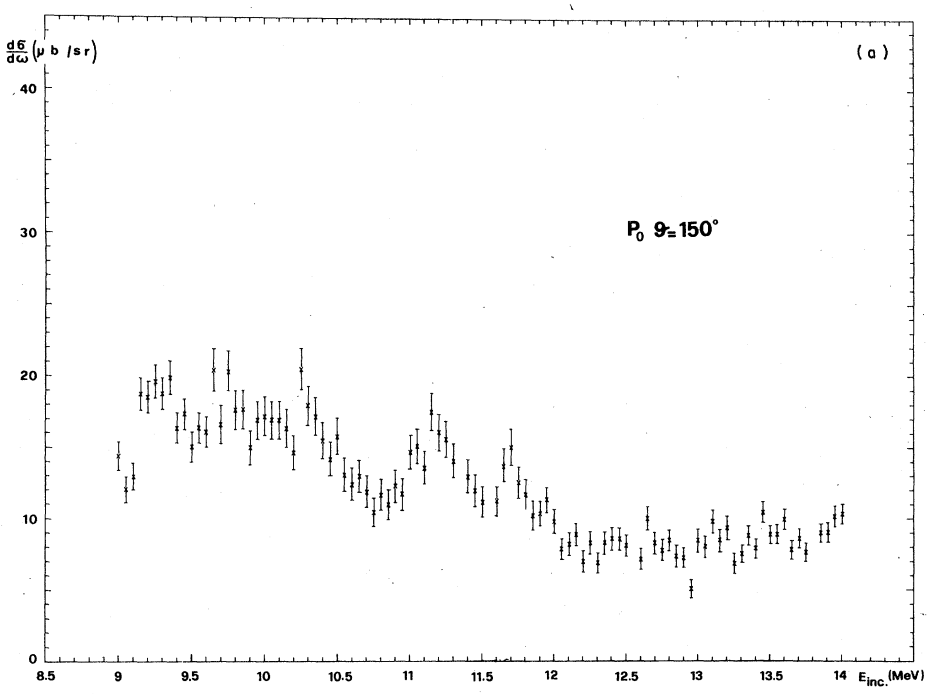
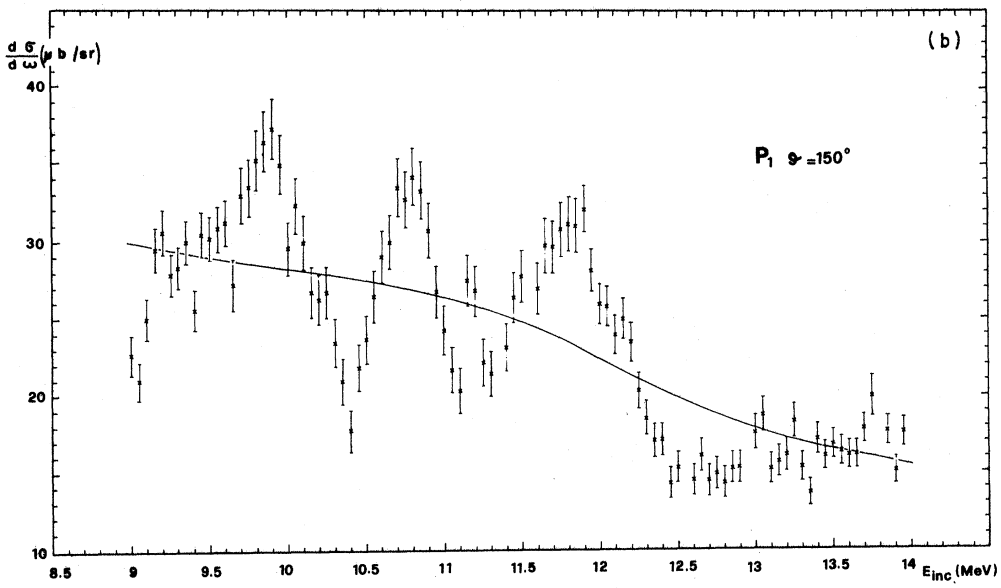


FIG. 3. (a)–(j) Excitation functions of ^{27}Al(^{3}He,p) reactions leading to a number of final levels of ^{29}Si. The laboratory angles are indicated in the figures.



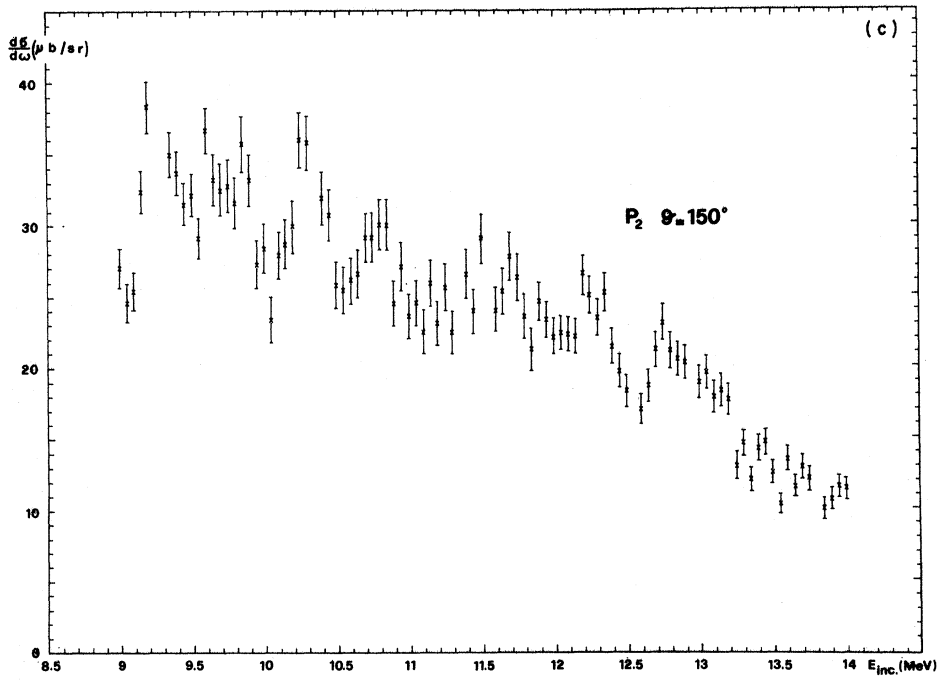
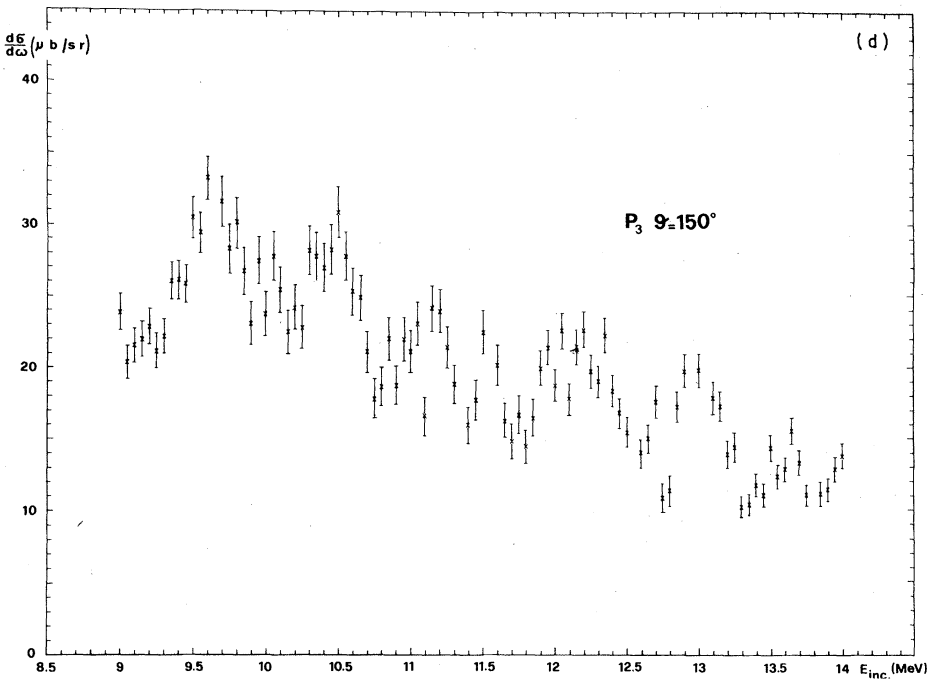
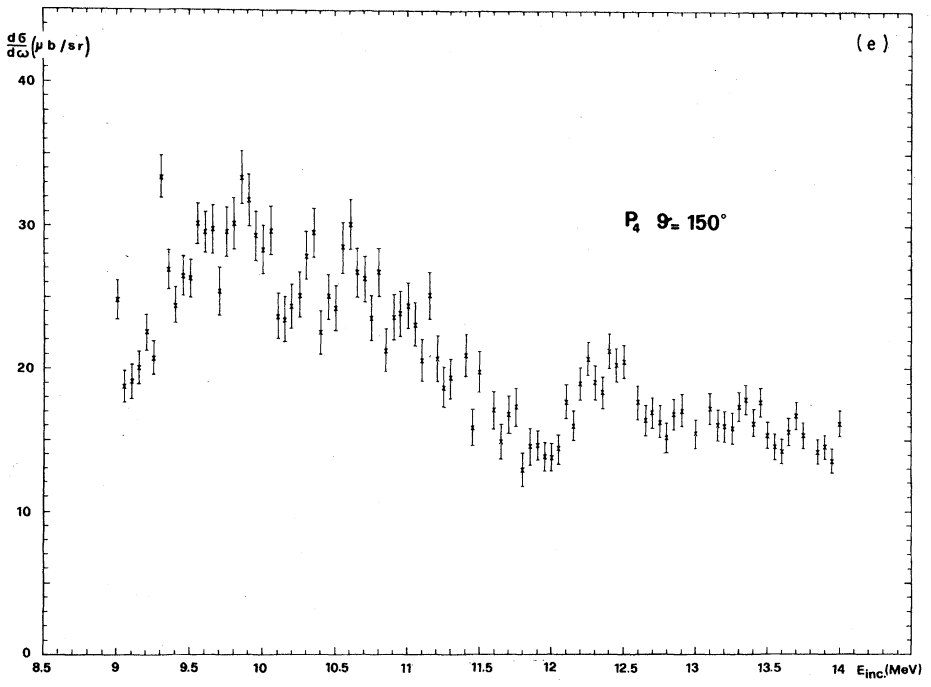


FIG. 3. *(Continued)*.





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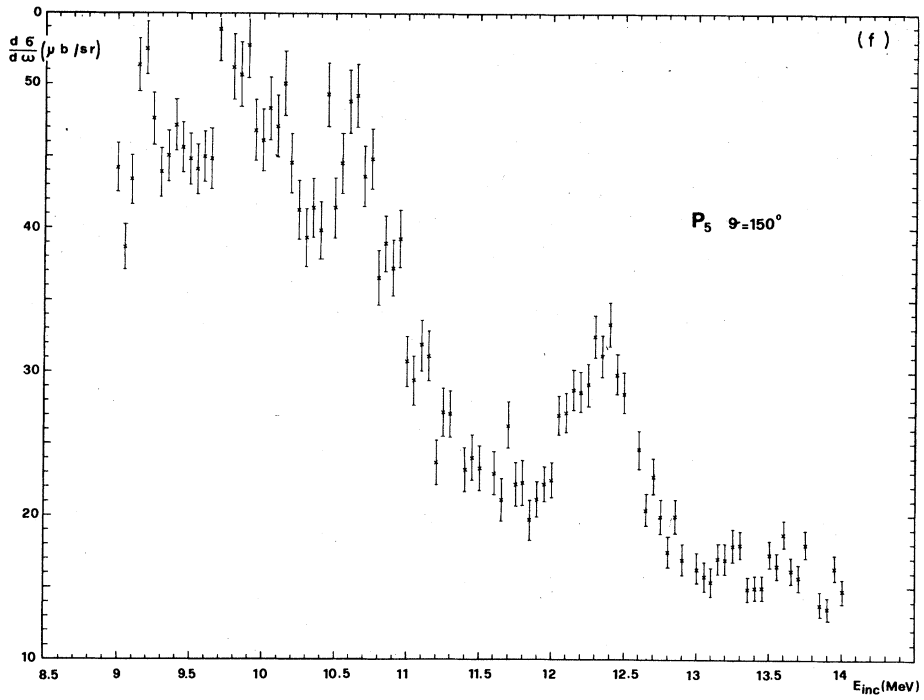

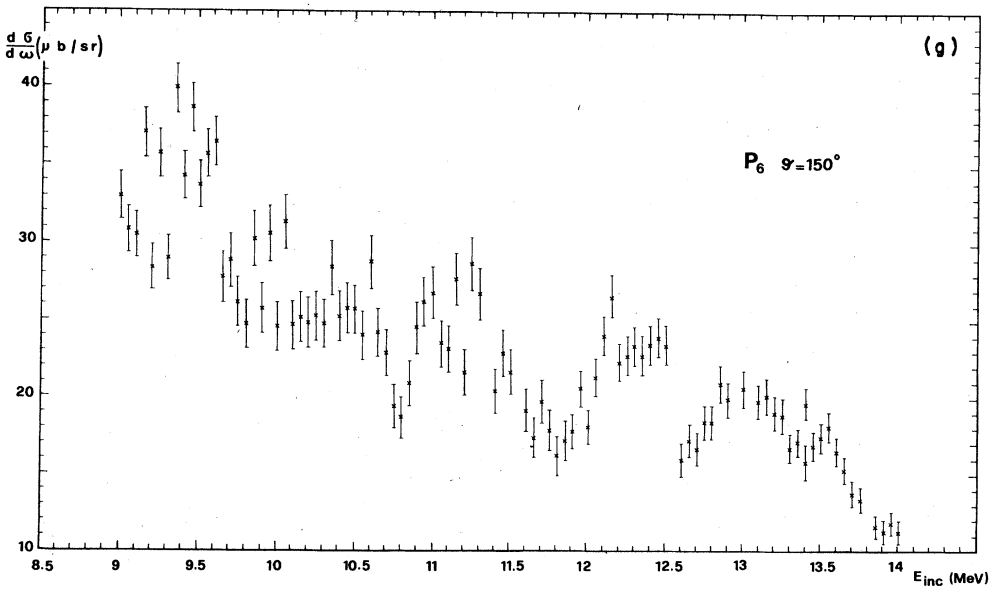

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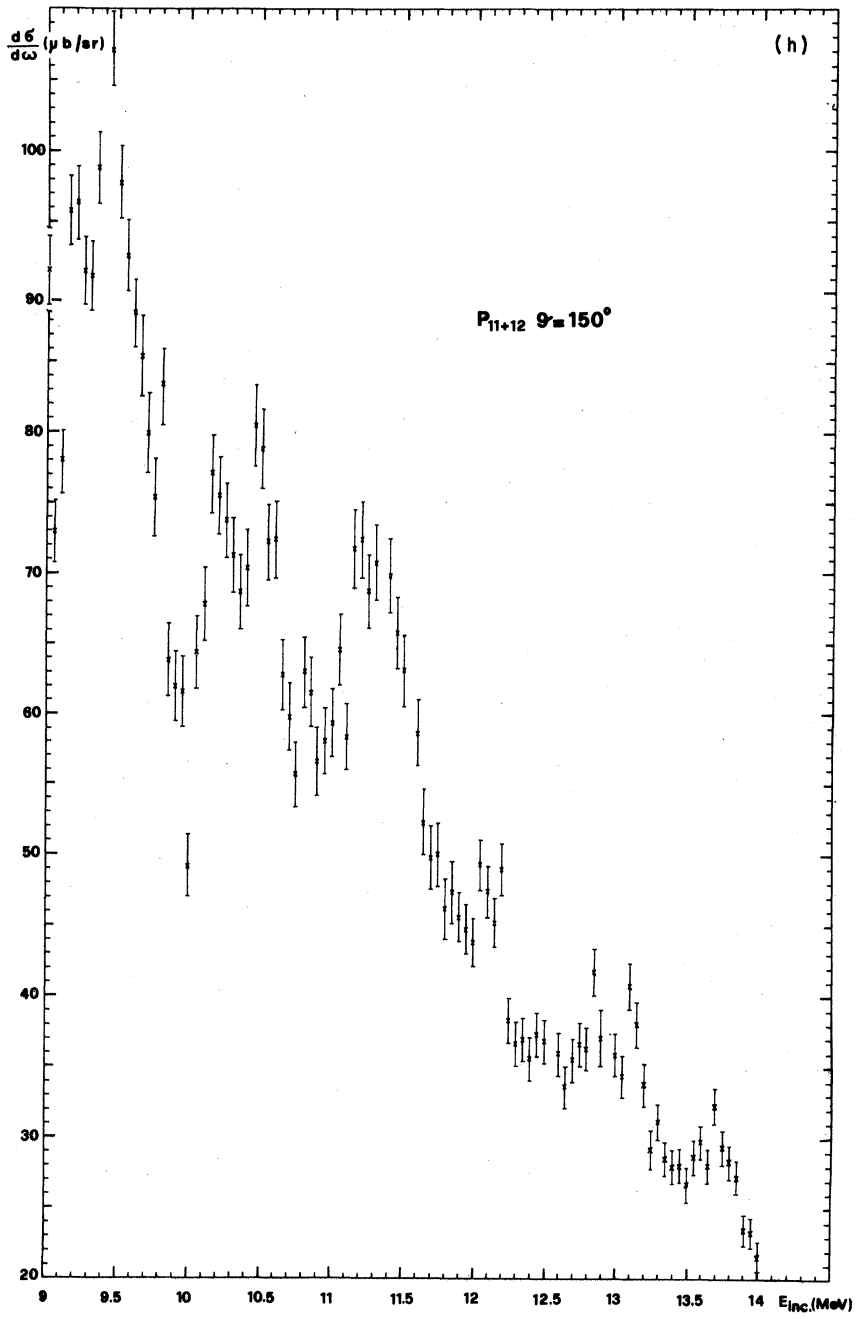

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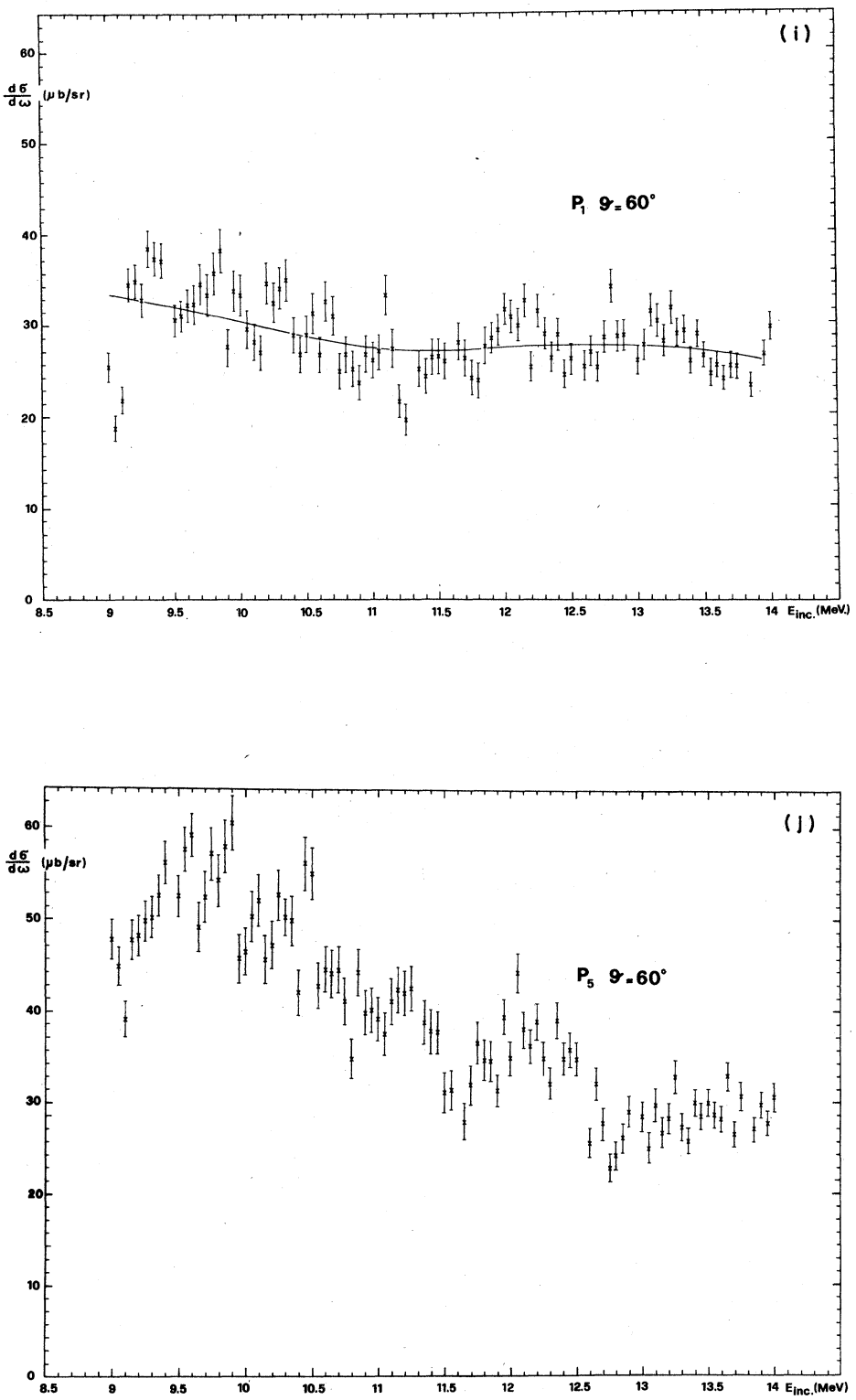

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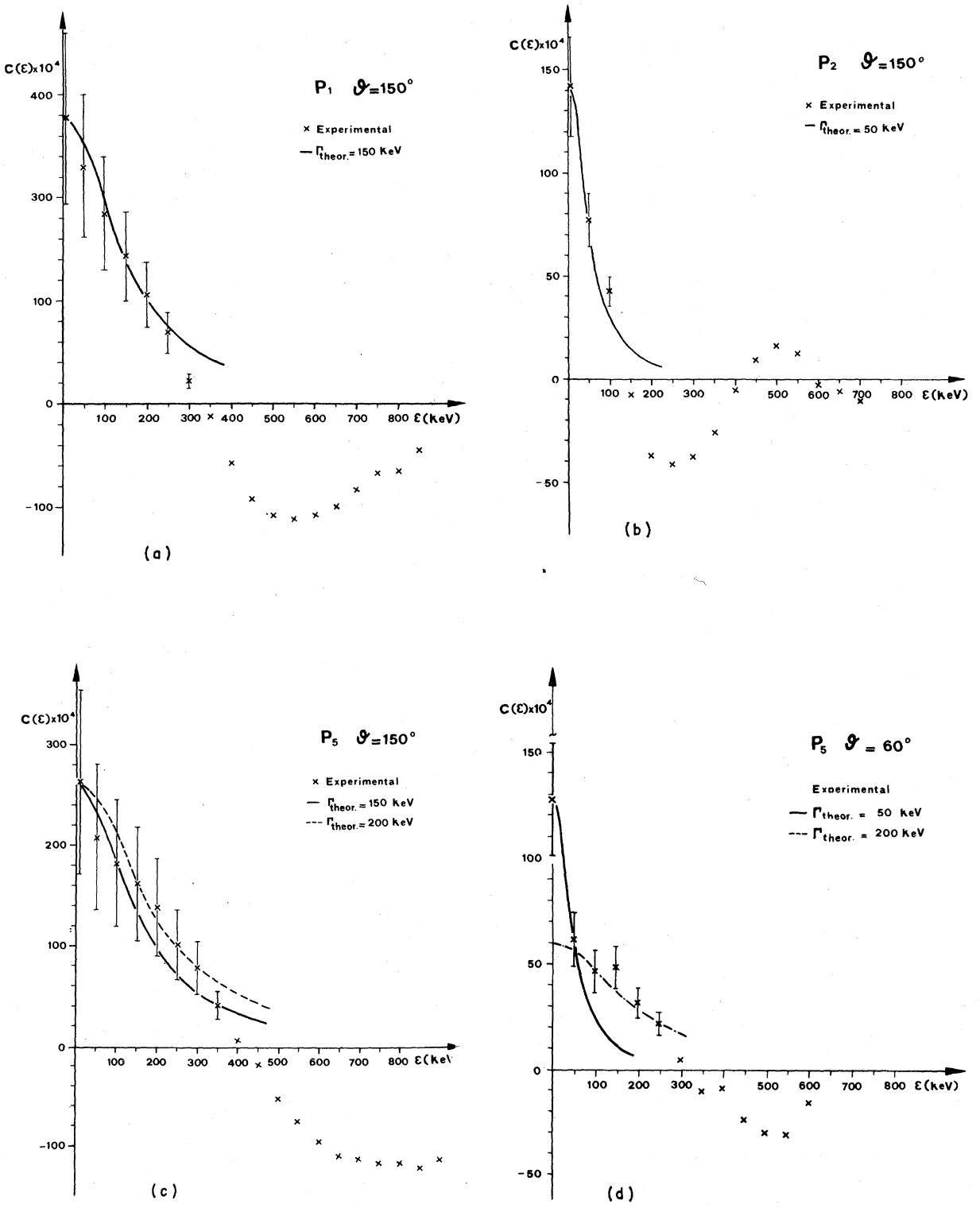

FIG. 4. (a)–(d) Autocorrelation functions calculated for some of the excitation functions. The curves shown together with the points are the theoretical shape (Lorentzian) corresponding to the Γ value indicated in each case.

ent values of the coherence energy are present, but at the present stage of the analysis this observation can be considered uncertain.

C. The proton spectrum

Figure 5 shows the proton spectrum at 120° taken at an incident ^{3}He energy of 13 MeV and integrated in steps of 1 MeV.

V. DISCUSSION OF RESULTS

The large differences in the values of the coherence energies obtained from the transition to different excited levels of the final nucleus ^{29}Si cannot be explained by means of pure compound nucleus formation and subsequent proton emission by the evaporation mechanism. Calculations on this point can be easily done in the framework of the Hauser-Feshbach theory. In the case of the ^{27}Al(^{3}He,p) reaction, it turns out that the Γ values corresponding to the various final levels can differ by no more than 10%, depending on the different final j values involved. It is therefore necessary to refer to another mechanism in order to explain the big difference in Γ values, and precompound emission is a natural choice.

In the case of the (^{3}He,p) reaction due to the low binding energy of ^{3}He we assume that in the first interaction with a nucleon in the target nucleus ^{3}He breaks up into its three components, at the same time exciting a particle from the occupied states and forming a hole.[13]

Considering the exciton model first, if we take $n_0=5$ as the initial exciton number and use for the model parameters the same ones used for the (n, p), (p,n), and (n,n') reaction calculations (single particle level density parameter "a" as given by slow neutron resonance measurements[14] and transition probability to the next stage as calculated by Gadioli *et al.*[15]) after the evaporation contribution has been summed up a curve is obtained for the proton spectrum which has an almost correct shape but which overestimates the cross-section value by a factor of about 2. However, the most dramatic disagreement is obtained when we compare the Γ width given by the exciton model with our experimental results. At an excitation energy of ~28 MeV in ^{30}P, as in our case, the exciton model Γ_5 is ~5 MeV or 20 times bigger than the one we found. It is worth noting that such a large value could not be detected in our experiments.

We can conclude that the fluctuations in the excitation function discussed herein cannot be explained on the basis of the exciton model. We therefore stop making comparisons with this model and begin to consider Feshbach's statistical multistep compound emission (SMCE). This theory is a complete one, so all the details of the reaction can be calculated: spectrum shape, angular distribution, and Γ value.

Two of us have done calculations based on the SMCE developing the computer code MUCOM for this purpose.[16] All the details necessary for calculation are contained in a paper to be published by Feshbach *et al.* from which we will quote only the most important points here.

The formula giving the cross-section value for a transition averaged over the final states (that is, corresponding to a transition leaving the residual nucleus with excitation energy U) is

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

where m is the index of the stage ($m=1$ means the first stage with 3 excitons, $m=2$ the second stage with 5 excitons, and so on until stage r, the equilibrium one). Γ_m is the total width of stage m. $\Gamma_m^{\downarrow}$ is the width of stage m going towards transition to the next stage. $\langle\rho_{\gamma\nu}(U)\Gamma_m^{\gamma\nu}\rangle$ is the width for particle emission into the continuum leaving the residual nucleus at excitation energy U and $\rho_{\gamma\nu}$ is the level density of the appropriately chosen residual nucleus states. ν stands for the exit mode and γ the quantum numbers of the state being considered. Γ_1/D_1 is the strength function for formation of the first stage, D_1 being the average distance of the corresponding states. $\Gamma_k^{\downarrow}/\Gamma_k$ is the "depletion term."

This formula has a structure quite similar to that of the exciton model, but the quantities involved are calculated in a very different way.

The level densities of the n-exciton states are calculated by following Ericson's formulas which use the equidistant single particle level model, as is often done in precompound calculations, but the spin distribution is introduced here with the result that level density is given by the following function

$$\rho_n(E,J)=\rho_n(E)R_J^n$$

where $\rho_n(E)$ is Ericson's formula and R_J^n is given by

$$R_J^n=\frac{(2J+1)}{\sqrt{\pi}n^{3/2}\sigma^3}e^{-(J+1/2)^2/n\sigma^2}$$

n being the exciton number and σ the usual spin cutoff parameter.

The quantity $\Gamma_n^{\downarrow}$ in the SMCE is given by $\Gamma_n^{\downarrow}=\langle\Gamma_{nJ}^{\downarrow}\rangle$ where the averaging function is $\rho_n(E,J)$ and

$$\Gamma_{nJ}^{\downarrow}=\frac{g(gE)^2}{2(n+1)}\frac{2\pi V_0^2}{A^2}\frac{1}{R_n(J)}\sum_{j_4Q}R_1(Q)F(Q)R_{n-1}(j_4)\times\Delta(Qj_4J), \quad (2)$$

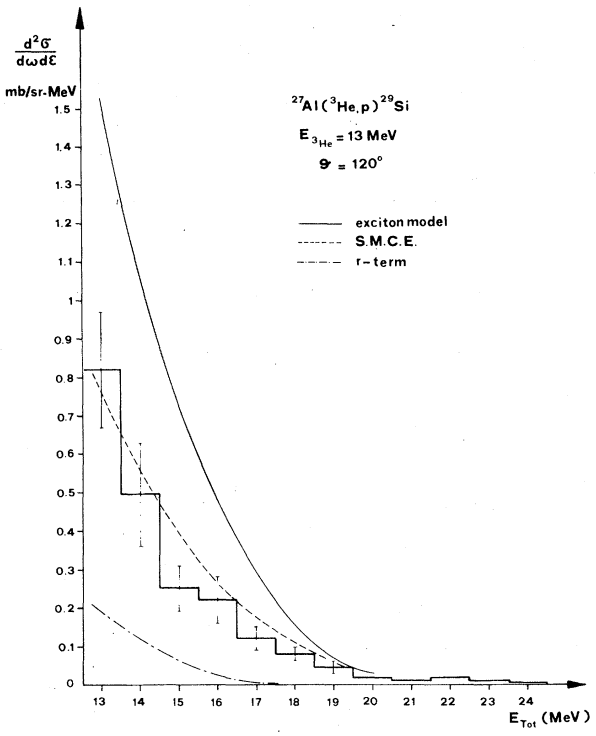

FIG. 5. Experimental spectrum of protons emitted from ^{27}Al(^{3}He,p)^{29}Si reaction at 13 MeV incident energy and $\vartheta_{lab} = 120°$. Curves calculated on the basis of exciton model and statistical multistep compound are also shown. The curve labeled r-term gives the contribution from the equilibrium stage as given by SMCE.

where g is the well-known single particle level density, E the excitation energy, V_0 the strength of the residual two-body interaction, taken as a δ function,[6,17] J is the total angular momentum of the initial channel configuration which is decomposed into the 2-exciton configuration with spin Q and the remaining $n-2$ excitons with spin j_4, $F(Q)$ is the angular momentum density of pair states and $n = 2m+1$. Calculations show that $\Gamma^{\downarrow}_{nJ}$ is practically J independent. We note that the parameter V_0 is a fundamental one in the SMCE and is also present as V_0^2 in $\Gamma^{\pi\nu}_m$ and $\Gamma_1^{(\ell)}$. We also note that when the transition to discrete states is studied as in this case formula (1) cannot be used because it is averaged over the final states. Actually, we expect a different contribution from the SMCE to different final levels, because the transition amplitude depends on the structure of the level involved.[6] Consequently, the presence of the SMCE in a transition to discrete levels should be observed first of all when a deviation of the transition amplitude from the rule of proportionality to $2j+1$ is noticed.

Table I shows in column 9 the transition intensities corresponding to the various proton peaks analyzed, integrated over the angle from 90° to 150° and over the energy from 8 to 13 MeV, in order to avoid the fluctuation effect. When the transition intensities are compared with the $2j+1$ rule large deviations are found. It is therefore natural to consider $\Gamma = 230$ keV as connected with emission from the first five-exciton stage in the SMCE.

Using formula (2), and taking for g the value given by slow neutron resonance counting[14] and by Ericson fluctuation analysis,[10] the experimentally measured Γ_5 value of 230 keV can be obtained by taking the value $V_0 = 0.70$ MeV which agrees quite well with the value found by Feshbach.[18] The uncertainty in the calculation due mainly to the uncertainty in the g value and to the error in the experimental determination of Γ is ±30%. The value of Γ_7, obtained by means of the same parameters, is found to be ~150 keV. The stages with an exciton number higher than 7 are all included in the equilibrium stage r, which has a theoretical width $\Gamma_r \simeq 55$ keV.

Comparison with the experimental values of Γ obtained from the different excitation curves shows substantial agreement with the calculations. It must be noted that mixed situations with contributions from different stages to the same proton peak must be expected. In these cases the different independently fluctuating contributions do not interfere, so that the fluctuation amplitude is reduced and the coherence energy of the resulting excitation function is difficult to predict.

On the basis of everything set forth above, it can be argued that the transition to the first and fifth excited levels of ^{29}Si seems to be dominated by the SMCE from the first stages. This is based on the large coherence widths and deviation from the $(2j+1)$ rule.

Finally, we compare the proton spectrum in absolute value with the SMCE prediction, that is, formula (1). In the case of the reaction being considered here, the calculation can be simplified by noting that the expression $(\pi/k^2)2\pi\Gamma_1^{(\ell)}/D_1$ is the cross section for formation of the first stage of the chain. Observing that the proton emission from ^{27}Al + ^{3}He has a higher cross section than the neutron and α emission and also that most of the proton emission is symmetric to 90°, we can conclude that almost all the reaction cross sections give rise to particle emission connected with the SMCE, evaporation included. More precisely, the anisotropic part can be calculated on the basis of the measured angular distributions. This part amounts to ~20% of the total at 13 MeV incident ^{3}He energy and for proton emission.

Following this line, we have calculated the emitted proton spectrum in absolute value, taking $(\pi/k^2)2\pi\Gamma_1^{(\ell)}/D_1$ as equal to 80% of the reaction cross-

section experimental value, and for the first stage the five exciton state ($m=2$). In this way the result does not depend on V_0, because it is present in both $\langle \rho_{\gamma\nu} \Gamma_m^{\gamma\nu} \rangle$ and Γ_m so that it is cancelled out. Other parameters are g, as usual, and r_0, the elementary nuclear radius, which appears in $\Gamma^{\dagger}$. Taking r_0 as equal to the value of 1.3 fm and giving g the same value as above, the curve shown in Fig. 5 is obtained. The fitting is quite good, considering that it is in absolute value. The uncertainty in the value of the parameters involved brings into this cross section's absolute value an uncertainty of ±50%. The shape of the spectrum instead depends only on the initial exciton number.

CONCLUSION

It is our opinion that what is set forth above shows rather convincingly the presence of the SMCE in the (^{3}He,p) reaction on aluminum, all details of which can be calculated by means of Feshbach's formulation.

It is also our opinion that this new emission mechanism has always been confused with statistical evaporation because of its symmetric to 90° angular distribution. Indeed, earlier results were often found showing excitation functions belonging to different final levels with coherence energy values differing more than allowed by the experimental errors.[19-22] We therefore believe that the experiment discussed herein gives proof of the existence of this emission mechanism for the first time.

ACKNOWLEDGMENT

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