Angular momentum role in cross-section energy coherence of heavy-ion dissipative collisions

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(Received 15 August 1988)

The dissipative excitation functions of the $^{19}F+^{63}Cu$ reaction have been measured in the energy range $E_{lab}=100$ to 108 MeV in 250 keV energy steps at angles $\theta_{lab}=10°,20°,30°,40°,50°$. The energy-coherence width of the cross section has been determined by means of the spectral-density method. The results concerning the $^{19}F+^{63}Cu$ and $^{28}Si+^{48}Ti$ reactions are compared to evidence the angular momentum effects on the cross-section autocorrelation function. The probability distribution of the cross section is considered in discussing the possible selective excitation of intermediate-system doorway states.

I. INTRODUCTION

After the experimental evidence[1–3] of cross-section fluctuations in heavy-ion reactions, much interest has been devoted both to gain more experimental information on the fluctuating behavior and to develop a theoretical framework in which all the experimental data could be comprehensively explained. Recently[4] it has been suggested that the presence of a significative amount of cross correlation between the excitation functions of the exit channels in a dissipative reaction can be explained by an extension of the Ericson theory. In this way the apparent contradiction between the fluctuation observation and the great number of unresolved independent exit channels contributing to the dissipative cross section can be overcome.

Actually the main problem in applying the statistical theory to dissipative reactions is the angular dependence of the cross-section autocorrelation function which has been observed at collision energies around the Coulomb barrier.[5] If the coherence energy was determined only by the mean lifetime of the decaying intermediate nucleus levels, it should be independent from the rotational motion and the same value should be obtained no matter at which angle it was measured. Two different explanations of the angular dependence have been proposed.[6,7] Through different procedures, both these models conclude that the cross-section–coherence-energy angular dependence is an angular momentum effect. Moreover, one of them[7] points out that the cross-section autocorrelation function in heavy-ion reactions does not have a Lorentz behavior versus energy.

In this paper the dissipative excitation function of the fragments produced in the $^{19}F+^{63}Cu$ collision in the energy range $E_{lab}=100$ to 108 meV is presented. The angular behavior of the cross-section coherence energy and the differential cross section of the $^{19}F+^{63}Cu$ and $^{28}Si+^{48}Ti$ reactions are compared to evidence the angular momentum effects on the cross-section autocorrelation function. The probability distribution of the cross section is considered in discussing the possible selective excitation of intermediate-system doorway states.

II. EXPERIMENTAL RESULTS AND ANALYSIS

The ^{19}F beam was provided by the Tandem XTU accelerator of the Laboratori Nazionali di Legnaro (Padova, Italy) and by the Tandem MP accelerator of the Laboratorio Nazionale del Sud (Catania, Italy). A self-supporting ^{63}Cu target of 45 $\mu g/cm^2$ thickness was used and all solid-state silicon and gas-solid-state silicon detector telescopes allowed charge identification of the emitted fragments by means of a standard ΔE-E technique. The excitation functions of $Z=4$–11 atomic number ejectiles were measured in 250 keV energy steps in the energy range $E_{lab}=100$ to 108 MeV at $\theta_{lab}=10°$–$50°$ angle in 10° steps.

In Fig. 1 the excitation functions of the $^{19}F+^{63}Cu$ reaction are reported at the five indicated emission angles for the various ejectile atomic numbers. The experimental points were determined taking into account only the damped part of the emitted fragment spectra,[1] so they represent the dissipative cross section. In all the panels of the figure the oscillating behavior is evident.

A fluctuation analysis was performed by means of the spectral-density method[8] and the coherence energy was determined. The results are summarized in Fig. 2 where the coherence energy Γ is reported versus the ejectile atomic number Z for the five emission angles considered here. The overall behavior of Γ vs Z is described by a flat bell-shaped curve centered at $Z=9$, corresponding to projectile-like fragments.

Figure 3 shows Γ vs the laboratory emission angle for $Z=4$–11. Taking into account the size of the error bars, the angular variation of the coherence energy appears very weak for almost all the fragments. Moreover, for $Z=4$–8 a constant value of 250 keV seems to reproduce the extracted values. Only the curves labeled $Z=9$ and $Z=10$ show a clear angular dependence. The former refers to projectile-like fragments and contains the largest determined Γ value, which was obtained at $\theta_{\rm lab}=30°$, very close to the grazing angle $\theta_{\rm G\,lab}=25°$.

This suggests a different character for the emission of the projectile-like fragments. Such a consideration is supported also by the observation of Fig. 4 where the average differential cross section is reported versus the emission angle for fragment atomic number $Z=4$–10. Each point has been determined by summing the measured yield over the incident energy range $E_{\rm lab}=100$ to 108 MeV. Almost all curves show a very broad peak or a shoulder around the grazing angle. This feature dominates the angular distribution of fragments having $Z=4$–8. The angular distributions of $Z=9$ and $Z=10$ fragments are strongly forward peaked, the presence of focusing being less evident. Then we can conclude that the excitation functions of Fig. 1, which are characterized by a coherence energy $\Gamma\approx250$ keV independent from the atomic number of the fragments as well from their emission angle, show angular distributions determined by the superposition of many partial waves. The time $\tau=\hbar/\Gamma$ corresponding to $\Gamma=250$ keV is about 2.6×10^{-21} s, comparable to the rotation period of the dinucleus, in the grazing configuration, which is estimated to be 2.5×10^{-21} s. Note that a coherence energy of 250 keV is close to the limit of sensitivity of our method of analysis due to the target thickness and to the overall energy measurement indetermination.

The emission of fragments having $Z=4$–8 takes a time

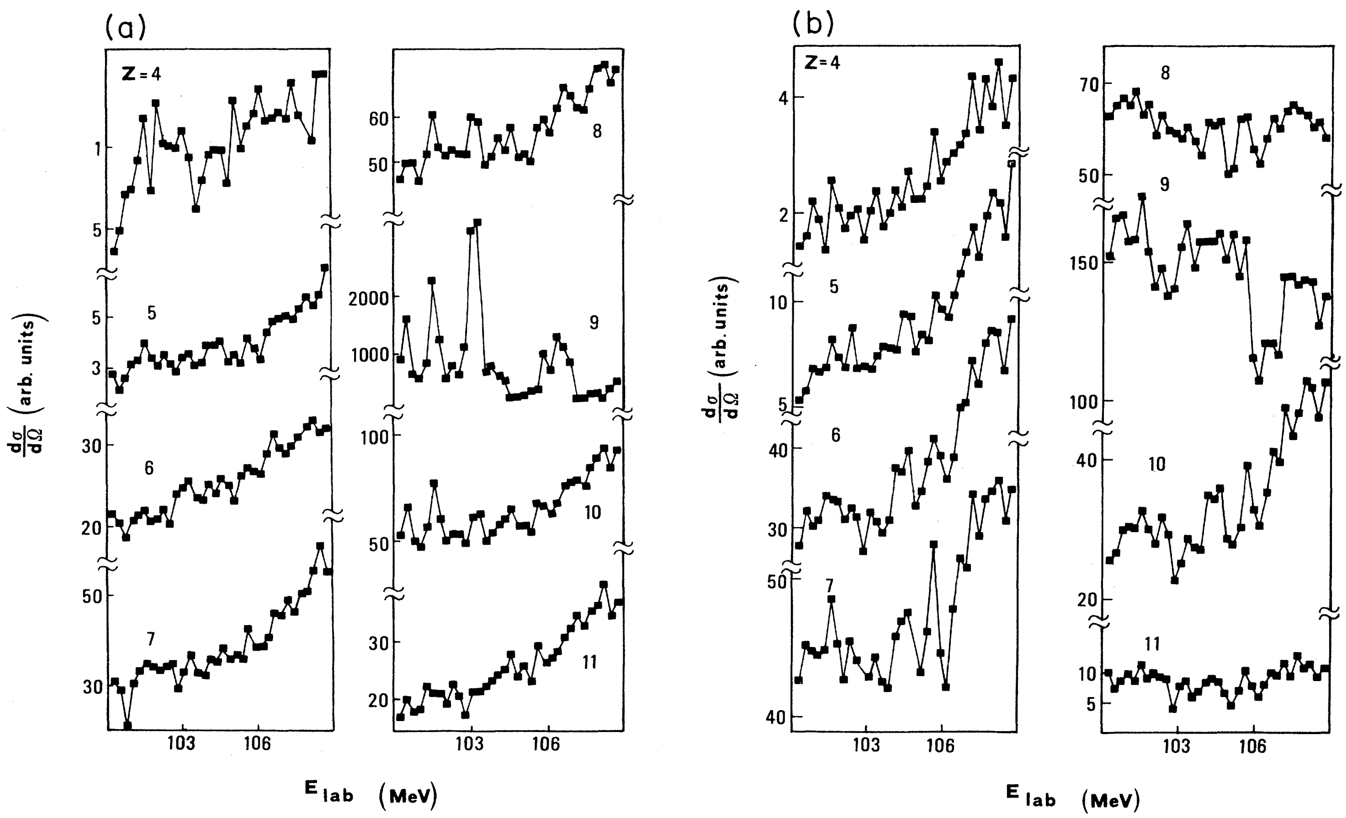

FIG. 1. (a) Excitation functions of the $^{19}F+^{63}Cu$ reaction at $\theta_{\rm lab}=10°$ for different fragment atomic numbers. The different curves are relatively normalized. (b) Same as (a) at $\theta_{\rm lab}=20°$. (c) Same as (a) at $\theta_{\rm lab}=30°$. (d) Same as (a) at $\theta_{\rm lab}=40°$. (d) Same as (a) at $\theta_{\rm lab}=50°$.

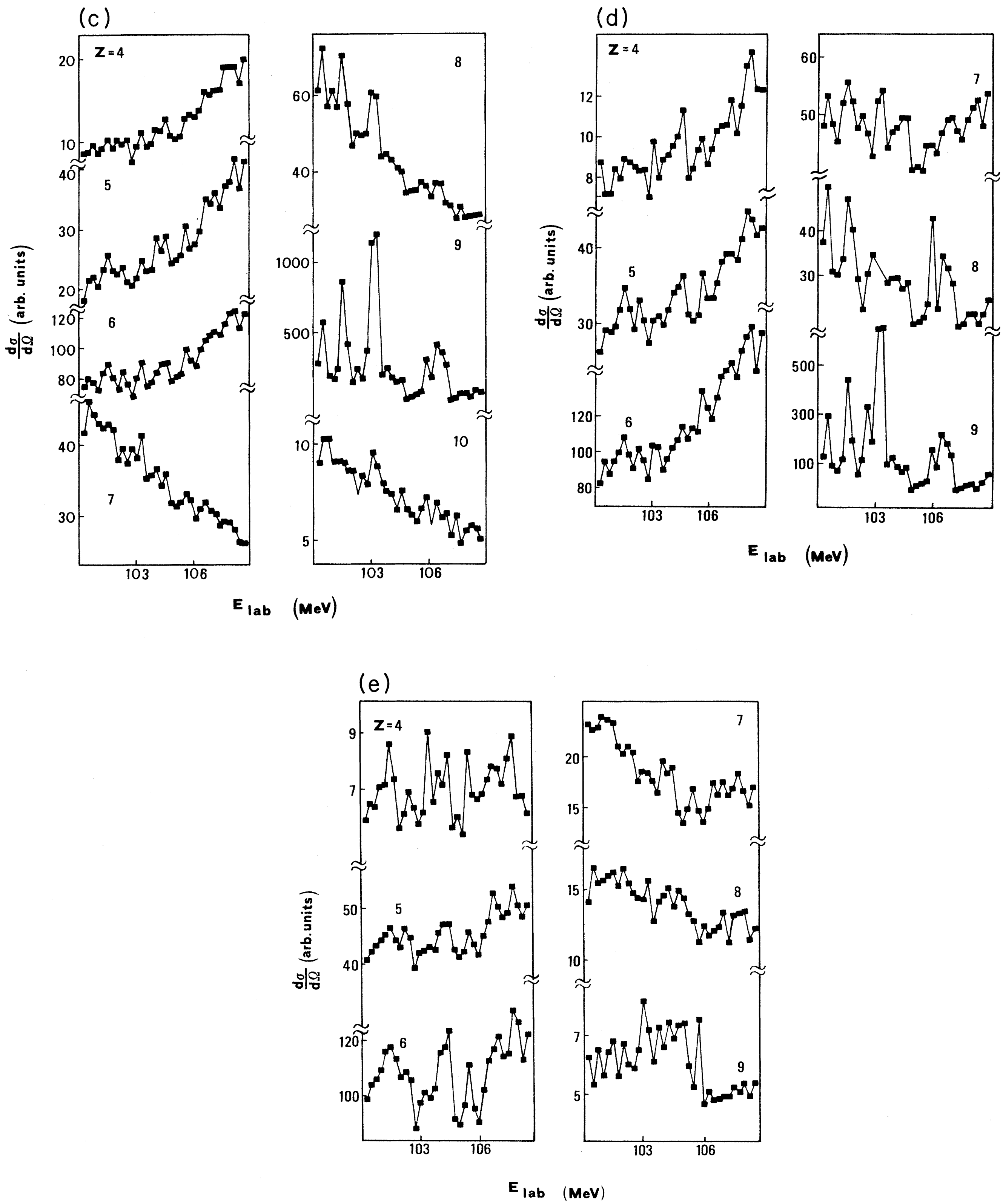

FIG. 1. (*Continued*).

equal to or longer than the rotation period of the interacting system. So the coherence energy of the corresponding excitation functions does not depend on the emission angle[7] in the observed angular range. The decaying states of the intermediate system are not fully equilibrated as it is evidenced by the asymmetric angular distributions of Fig. 4. The reaction mechanism is typical of mixed reactions, and the observability of cross-section fluctuations is due to the significative amount of cross correlation between the reaction amplitudes of the many unresolved exit channels.[4]

The angular distributions of $Z=9$ and $Z=10$ fragments show an exponential decrease with the emission angle. Such a behavior is typical of peripheral collisions with a small mass transfer when only a narrow interval of l values contributes to the reaction. According to the Strutinsky model[9] in the reaction amplitude

$$f(\theta)=\frac{1}{2ik}\sum_{l}(2l+1)\eta_l e^{2i\delta_l}P_l(\cos\theta)\ , \qquad (1)$$

a Gaussian behavior

$$\eta_l=\eta_{l_0}e^{-[(l-l_0)/\Delta l]^2} \qquad (2)$$

is given to the amplitude, δ_l being the phase shift and l_0 the central angular momentum value of the incident wave packet. Δl is a parameter determined by the dispersion of

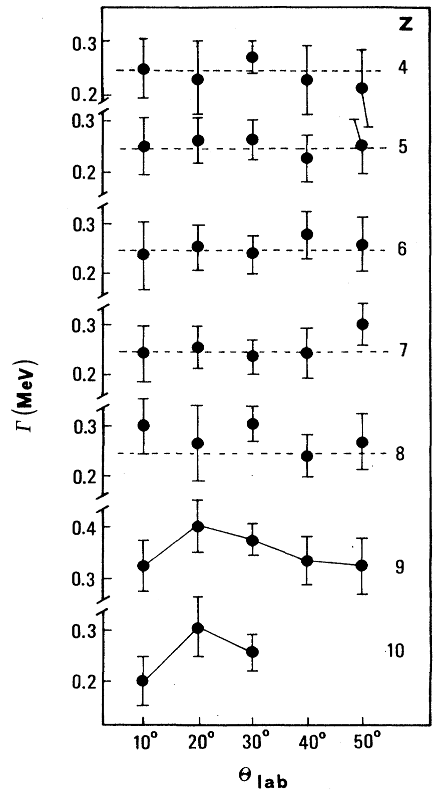

FIG. 3. Coherence energies extracted from the excitation functions of Figs. 1(a)–(e) vs emission angle for different fragment atomic numbers.

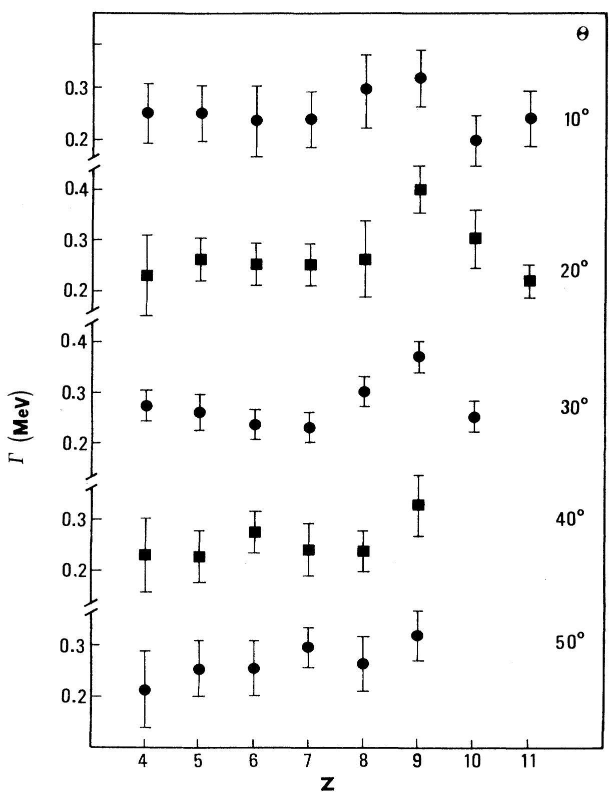

FIG. 2. Coherence energies extracted from the excitation functions of Figs. 1(a)–(e) vs fragment atomic number.

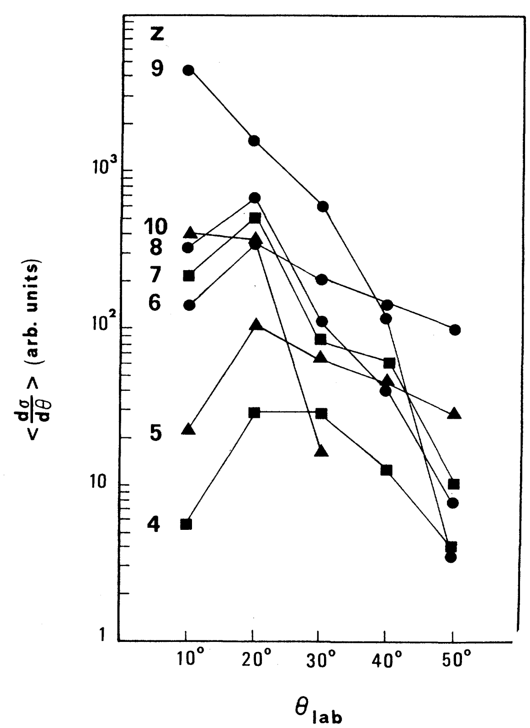

FIG. 4. Angular distributions of the average differential cross section for the $^{19}F+^{63}Cu$ reaction.

the contributing l values. With this assumption the angular distribution becomes[10]

$$\frac{d\sigma}{d\theta} \propto e^{-(\theta-\theta_0)^2/\xi^2} + e^{-(\theta+\theta_0)^2/\xi^2} , \tag{3}$$

where θ_0 is the diffusion angle corresponding to l_0 and ξ is a dispersion parameter. The second term in the right-hand side (rhs) of (3) takes into account the farside contribution. If the angular distribution is sharply peaked around the angle θ_0 it will show an exponential decrease

$$\frac{d\sigma}{d\theta} \propto e^{-(\theta-\theta_0)^2/\xi^2} . \tag{4}$$

The angular dispersion parameter ξ contains the contribution of both the quantal and the dynamical dispersion[10]

$$\xi^2 = \frac{2}{\Delta l^2} + \frac{2}{\lambda_c^2} . \tag{5}$$

The quantal dispersion is determined by Δl defined in (2) which can be estimated by means of the approximate relation[9]

$$\Delta l \sim \frac{d\, l_0}{R_{\text{int}}} , \tag{6}$$

where $R_{\text{int}} = (R_1 + R_2)$ is the interaction radius of the dinucleus and d is the nuclear surface thickness which can be assumed $\sim 4a$, a being the corresponding diffuseness. For the present reaction, taking $a = 0.65$ fm, $r_0 = 1.2$ fm, and $l_0 \approx 35$, one obtains $\Delta l \approx 12$. In this approximation l_0 has been assumed equal to the grazing angular momentum.

In the second term of (5) the coherence length takes

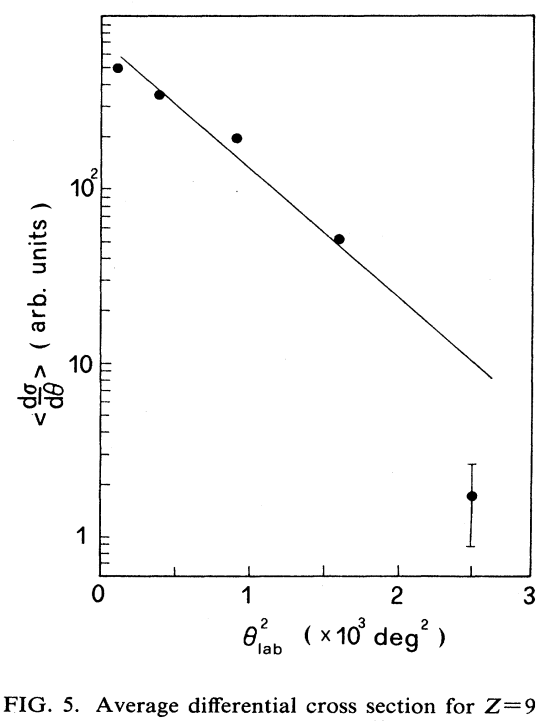

FIG. 5. Average differential cross section for $Z = 9$ ejectiles versus square of emission angle for the $^{19}F + ^{63}Cu$ reaction.

TABLE I. Results from the analysis of the $^{19}F + ^{63}Cu$ reaction.

Γ (MeV)	$\delta\lambda_c$	δ	$\lambda_{\text{exp}}/\lambda_c$
0.4	32.9	10	1.03
0.375	30.9	9	0.99
0.325	26.7	8	1.01

the form

$$\lambda_c = \frac{2\mathcal{J}}{\hbar \delta \tau} , \tag{7}$$

$\mathcal{J}$ being the dinucleus moment of inertia, τ the interaction time, and δ the angular momentum correlation length which measures the width of the dinucleus wave packet. In Fig. 5 the angular distribution of the $Z = 9$ fragments is reported vs $|\theta - \theta_0|^2$ (we assumed $\theta_0 = 0°$ due to the particular shape of the distribution). The solid line is a linear least-squares fit of the function (4) to the experimental points in the figure. By this procedure the value $\xi = 0.42$ was determined for the angular dispersion parameter which corresponds, through the (5), to an experimental correlation length $\lambda_{\text{exp}} = 3.4$.

Relation (7) allows an estimation of the expected value of the correlation length considering δ as a free parameter and taking for $\mathcal{J}$ the moment of inertia of the dinucleus ($^{19}F + ^{63}Cu$). The time τ can be evaluated through the indetermination relation $\tau = \hbar/\Gamma$, using for Γ the values reported in Fig. 3 for $Z = 9$. As can be seen in Table I, the values of λ_c compare very well to the determined λ_{exp} if a value between 8 and 10 is given to the parameter δ. These values are quite consistent with the preequilibrium character of the reaction considered here as in the CN limit $\lambda_c \to 0$, which means complete incoherence among partial waves.

The overall consistency of the features of $Z = 9$ angular distribution with the Strutinsky model for transfer reactions and the determined angular momentum correlation length supports the evidence for a different character of the emission of projectile-like fragments with respect to other fragments. The number δ of partial waves contributing to the reaction amplitude (1) determines the angular behavior of the autocorrelation function through the function[7]

$$\Gamma^{\pm}(\theta) = \Gamma_E - \frac{k}{\delta^2}(\theta \pm \theta_0) , \tag{8}$$

Γ_E being the coherence energy defined according to the Ericson theory[12] and k a parameter which depends on the angular velocity and on the first-order l derivative of the deflection function. One can note that if $\delta \to \infty$, i.e., in the CN limit, the (8) reduces to the standard Ericson form (generally, the greater the δ value, the weaker the angular dependence).

III. COMPARISON TO THE $^{28}Si + ^{48}Ti$ REACTION

In this section the results relative to the $^{19}F + ^{63}Cu$ are compared to those of the $^{28}Si + ^{48}Ti$ reaction.[2,4] In both these reactions the general behavior of the coherence energy versus the fragment atomic number is described by a more or less wide bell-shaped curve. This suggests a shorter interaction time or a greater emission probability for the projectile-like fragments. In Figs. 6(a) and 6(b) the angular distributions $d\sigma/d\Omega$ of the $^{28}Si+^{48}Ti$ at 100 MeV incident energy and the coherence energy Γ are reported versus emission angle. The data are from Ref. 11. It is apparent that the strong peaking of the angular distributions around the grazing angle is indicative of a narrow band of contributing partial waves. Then the cross section can be described by means of expression (4), assuming $\theta_0=\theta_G$. In Fig. 7 the angular distribution of fragments having $Z=13$ is reported vs $|\theta-\theta_G|^2$ for $25°\le\theta\le 40°$. The solid line is a least-squares fit to the experimental data of the function

$$\frac{d\sigma}{d\theta}\propto e^{-(\theta-\theta_G)^2/\xi^2},$$

corresponding to an angular dispersion parameter $\xi=7.8\times10^{-2}$. By means of expression (6) a value of $\Delta l\approx 12$ is determined also for the present reaction. Then from (5) one can verify that for the considered reaction

$$\xi^2<\frac{2}{\Delta l^2}, \tag{9}$$

thus supporting the evidence that the width of the angular distribution is completely accounted for by the quantal dispersion alone. In such a case the relation

$$\Delta l \ll \lambda_c \tag{10}$$

should hold.

Following the same procedure as in the preceding section, expression (7) allows us to determine the values of $\delta\lambda_c$ reported in Table II. As the relation $\lambda_c>12$ should hold, one obtains $\delta<3$ in all the cases considered.

From these results, according to the conclusions of the preceding section, a pronounced angular dependence of the coherence energy should be expected for almost all the fragments as their angular distributions have a very similar behavior. This is consistent with the general features of Γ shown in Fig. 6(b). The greater Γ's or the shorter interaction times are indicative of a less equilibrated intermediate system in the $^{28}Si+^{48}Ti$ with respect to the $^{19}F+^{63}Cu$ reaction.

Another important quantity to be considered in studying the statistical properties of the cross section is the number of unresolved final channels contributing to the dissipative cross section. In the standard Ericson theory, in the case of a pure CN reaction, the number of final channels dumps the cross-section fluctuations, then the autocorrelation function[12]

$$C(\varepsilon)=\frac{\langle\sigma(E)\sigma(E+\varepsilon)\rangle}{\langle\sigma(\varepsilon)\rangle\langle\sigma(E+\varepsilon)\rangle}-1$$

becomes

$$C(\varepsilon)=\frac{1}{N_{\text{eff}}}\frac{\Gamma^2}{\Gamma^2+\varepsilon^2}.$$

The effective number of final channels N_{eff} can be evaluated from the inverse of $C(\varepsilon=0)$. In the actual case considered here, the autocorrelation function could not be of

TABLE II. Results from the analysis of the $^{28}Si+^{48}Ti$ reaction.

Γ (MeV)	$\delta\lambda_c$	δ
0.5	38.6	<3
0.45	34.7	<3
0.42	32.4	<3

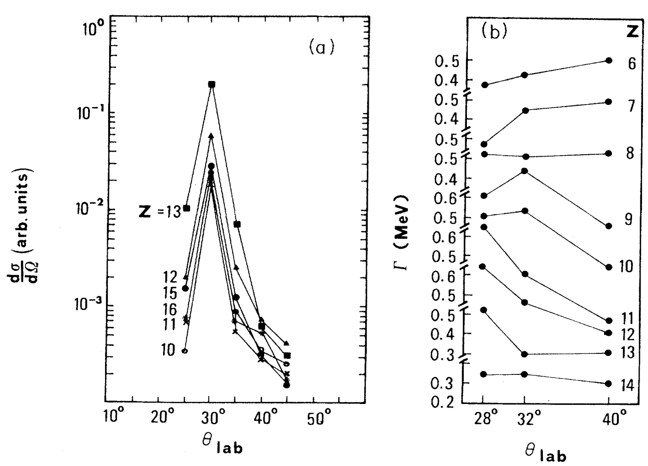

FIG. 6. (a) Angular distributions corresponding to different fragment atomic numbers for the $^{28}Si+^{48}Ti$ reaction at $E_{\text{lab}}=130$ MeV. (b) Angular behavior of the coherence energies for the $^{28}Si+^{48}Ti$ reaction.

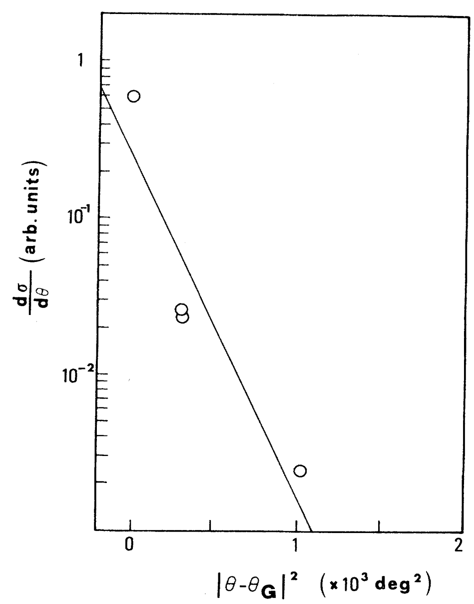

FIG. 7. Differential cross section for the $^{28}Si+^{48}Ti$ reaction vs $|\theta-\theta_G|^2$ at $E_{\text{lab}}=130$ MeV. θ_G is the grazing angle.

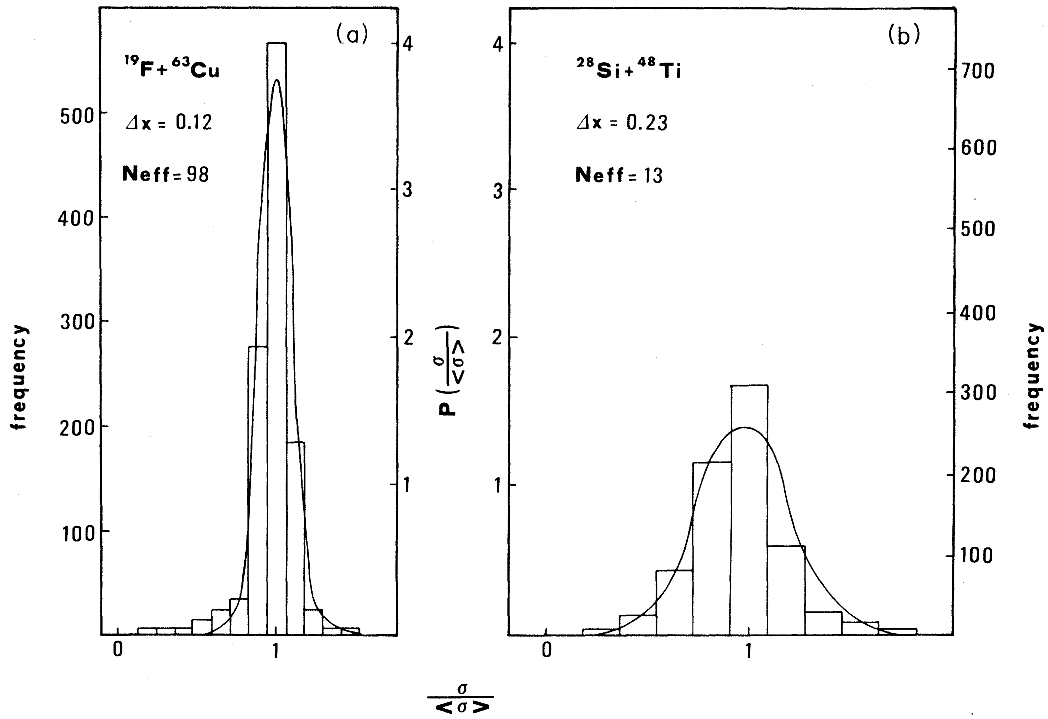

FIG. 8. Experimental frequency distribution of the cross section (a) for the $^{19}F+^{63}Cu$ reaction and (b) for the $^{28}Si+^{48}Ti$ reaction. The bin width Δx and the number of effective final channels $N_{\rm eff}$ are indicated.

pure Lorentz shape, so it is advisable to determine $N_{\rm eff}$ from the probability distribution of the cross section[13]

$$P\left[\frac{\sigma}{\langle\sigma\rangle}\right]=\frac{N_{\rm eff}}{N_{\rm eff}-1}\frac{1}{\langle\sigma\rangle}\times\left[\frac{\sigma}{\langle\sigma\rangle}N_{\rm eff}\right]^{N_{\rm eff}-1}e^{-N_{\rm eff}(\sigma/\langle\sigma\rangle)} . \quad (11)$$

In Figs. 8(a) and 8(b) the experimental frequency distribution of the cross section is reported as an histogram for the $^{19}F+^{63}Cu$ and $^{28}Si+^{48}Ti$ reactions, respectively. To increase the statistical accuracy of the analysis, the experimental data of each reaction have been considered all together and ordered in bins whose widths Δx has been taken equal to the average

$$\Delta x=\left\langle\frac{\sigma-\langle\sigma\rangle}{\langle\sigma\rangle}\right\rangle$$

performed over all the points, $\langle\sigma\rangle$ being the average cross section used in determining the coherence energy Γ.[8] Solid lines are fits of Eq. (11) to the histograms and correspond, respectively, to $N_{\rm eff}=98$ and 13 for the $^{19}F+^{63}Cu$ and $^{28}Si+^{48}Ti$ reactions. As the energy step and the overall resolution of the measurements relative to the two reactions are very similar, their effective channel numbers are directly comparable. These results could be considered in agreement with the more pronounced preequilibrium character of the latter reaction as it was pointed out by its shorter interaction times and angular distributions sharply peaked around the grazing angle. The small number of effective final channels makes such a reaction a natural candidate for investigating the existence of some selective excitation of special intermediate-system states, such as giant resonances, acting as doorways for the reaction. This effect should be searched for by measuring the multipolarity of high-energy γ rays emitted in coincidence with the fragments.

IV. SUMMARY AND CONCLUSIONS

The cross-section energy correlation width in dissipative heavy-ion reactions is not determined only by the energy indetermination, or by the mean lifetime, of the intermediate-system states excited in the collision. The presence of a narrow window of angular momenta effective in the reaction amplitude introduces a dependence on the emission angle. This effect, on which are based theories recently formulated[6,7] to explain the experimental evidence[5] of the angular dependence of Γ, has been clearly evidenced in the present paper. The angular behavior is similar in all the considered reactions, though some features are not equally shown by all of them. In fact, generally, the greater the difference between the observed fragment and the projectile atomic number, the weaker the coherence-energy angular dependence. In some cases the angular distributions are well described by reaction amplitudes in which the contributing angular momenta have a Gaussian distribution around some reference angle θ_0. Ejectiles showing this feature are characterized by Γ having a significactive angular dependence. Angular distributions determined by the incoherent superposition of many partial waves are associated to Γ independent both on the angle and on the atomic number. In such cases the emission takes an interaction time at least of the same order of magnitude of the dinucleus rotation period in the grazing configuration.

All this information can be summarized in the following description of the collision process. In the early stages of the interaction the colliding ions assume a dinuclear configuration whose features are determined by the relative motion through the orbital angular momentum L. The dissipation of the rotational energy by intrinsic excitation of the fragments, or by light particle's evaporation, leads the intermediate system in more equilibrated configurations no more characterized by a narrow interval of allowed L values. In this situation the decay cross section has a coherence energy which is determined only by the mean lifetime of the excited levels; then it does not have any significative angular dependence. Only the cross section for the emission of fragments before the dissipation of rotational energy has a coherence energy which depends on the orbital angular momentum or on the emission angle. Such a feature is exhibited by almost all the fragments produced in the $^{28}Si+^{48}Ti$ reaction which is also characterized by a very limited number of effective final channels, 1 order of magnitude smaller than the one of $^{19}F+^{63}Cu$ reaction. This may be an evidence for some selective excitation of special intermediate system states acting as doorways for the reaction. Recently[11] the possible giant-resonance nature of these excited states has been considered.

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