Long-range correlation widths in light heavy-ion nuclear reactions

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Evidence for doorway-state fluctuations in the $^{12}C+^{28}Si$ system is presented. It is found that the correlation widths extracted from the fluctuating excitation functions of this reaction and other cases either measured in our previous work or found in the literature are up to 1 order of magnitude larger than the traditional compound-nucleus widths; moreover, they exhibit a completely different energy and mass-number dependence. All these features are well interpreted within the framework of the statistical multistep compound theory of preequilibrium reactions.

I. INTRODUCTION

Eight years ago we started an experimental program aimed at investigating multistep compound effects in light and subsequently in heavy-ion-induced reactions. Six different reactions were studied through detailed measurement of their various experimental aspects: spectra, angular distributions, and, in particular, excitation functions. The main result was probably the discovery of "long-range" correlation widths in the excitation functions of several low-lying residual nucleus levels. This discovery, which was thoroughly discussed in previous papers,[1-4] was interpreted as being due to the overlapping of doorway states, i.e., simple, few-degrees-of-freedom configurations, populated by the composite system on its way towards equilibration. This effect received its natural interpretation in the framework of the statistical multistep compound emission (SMCE) mechanism,[5] which was first proposed when our program was begun in 1980 and has now been sufficiently tested in various experimental cases.

In this reaction mechanism the equilibration process leading to compound-nucleus (CN) formation is described as a sequence of quasiequilibrium stages of increasing complexity. These are qualitatively similar to the CN state, but with shorter lifetimes, due to the additional presence in the total decay width of a given stage of the probability for internal transition to the next, more complex stage (the "damping width"). The basic idea supporting interpretation of the experimentally measured "long-range" correlation widths in terms of such multistep compound widths is that if the densities of the levels were high enough within a given stage so that they overlapped, interference might occur and give rise to fluctuations in the excitation functions of isolated levels, similar to the traditional Ericson fluctuations, but characterized by a larger coherence width. Calculations done on the basis of a p-h representation of the nuclear excitation process[1] do in fact show that the condition $\Gamma_n > D_n$ is well satisfied even for the most simple doorways (i.e., for small values of the "exciton number" n).

To be more specific, in the reactions we have studied so far composite systems of mass number 28–30 at ≈ 30 MeV excitation energy formed by different projectiles gave rise to compound-nucleus and doorway-state coherence widths of ≈ 50 and $\approx 200-350$ keV, respectively. These results were well reproduced by calculations based on the SMCE theory. Moreover, the scattering of the doorway-state width values can be explained in terms of their dependence on the "quality" of the doorway states themselves, associated with the type of incident projectile. (The "complexity" of the projectile does in fact determine n_0, the number of initial degrees of freedom of the multistep compound chain.)

Despite its general success and the number of papers published about it, this idea still seems far from being generally accepted. The reason for this could well be that in the case of light heavy-ion reactions, where most recent work has been concentrated, interpretation of the structures measured in the excitation functions as well as their statistical analysis is complicated by the presence of the well-known molecular resonances. As will be shown in Sec. IV, however, many authors in their search for isolated molecular resonances do not find a convincing interpretation of these structures in such terms. The main difficulty seems to be that these "anomalous" structures have a "statistical" behavior (negligible correlation among different outgoing channels and/or emission angles), but at the same time the extracted correlation width is so large that interpretation in terms of CN fluctuations does not seem to be possible. It has been shown in previous papers and is stressed again in this one that these are precisely the features expected in doorway-state fluctuations. Confirmation of such a hypothesis is, therefore, now our first goal. The second reason for the experiment reported here is that CN and doorway-state widths are expected to have a rather different mass and energy dependence, as will be shown in Sec. IV; by choosing a system with a mass different from those measured previously we can therefore add another important check to our interpretation. Consequently, what we have chosen to measure is the $^{28}Si(^{12}C,\alpha)$ reaction exciting the ^{40}Ca

composite system in the energy range 36.6–41.5 MeV.

Sections II and III are devoted to a presentation of the experimental results, while a discussion of mass number and energy dependence of the widths extracted from our work and from data existing in the literature is given in Sec. IV.

II. DESCRIPTION OF THE EXPERIMENT

The $^{28}Si(^{12}C,\alpha)^{36}Ar$ excitation functions were measured from 33.350 to 40.250 MeV (lab) partly at Legnaro and partly at Catania Tandem Laboratories. The energy step was 150 keV in the laboratory system, corresponding to 105 keV in the c.m. system; this was considered the best compromise between the need to limit beam time and the need to follow structures several hundreds of keV's wide in sufficient detail. The targets were enriched in ^{28}Si and had thicknesses ranging from 50 to 100 $\mu g/cm^2$, which give rise to an energy loss of 105–210 keV (c.m.) of the incident carbon beam. α particles were detected by means of a solid-state telescope placed at 30° (lab); the thickness of the ΔE detector (100 μm) was chosen in order to eliminate the pulses due to elastic scattering and other heavy products via a coincidence requirement with the E detector (1000 μm). The angular acceptance of the telescope was $\approx 4.5°$.

III. INTERPRETATION OF THE EXPERIMENTAL RESULTS

The generally low cross section of the $^{28}Si(^{12}C,\alpha_{0-5})$ reaction (of the order of 1–10 μb/sr) forced us to use a rather large solid angle and target thickness in order to get a reasonable yield; the final resolution did not therefore allow separation of the α_{2-5} levels of the ^{36}Ar residual nucleus. We present, in Fig. 1, the excitation functions for α_0, α_1, and the quadruplet α_{2-5} at 30°, all of which exhibit large, uncorrelated structures.

For their interpretation, the first possibility considered was that they were due to CN (Ericson) fluctuations. This hypothesis could be easily verified by comparing the widths calculated using the CN Hauser-Feshbach theory with those extracted from an autocorrelation analysis of the excitation functions. The results of such an analysis done with the statistical methods used in previous papers[2–4] are shown in Table I and Fig. 2. The most striking result is the large difference in Γ values obtained from transition to the g.s. of ^{36}Ar compared with that of other groups. The width extracted from this level is much

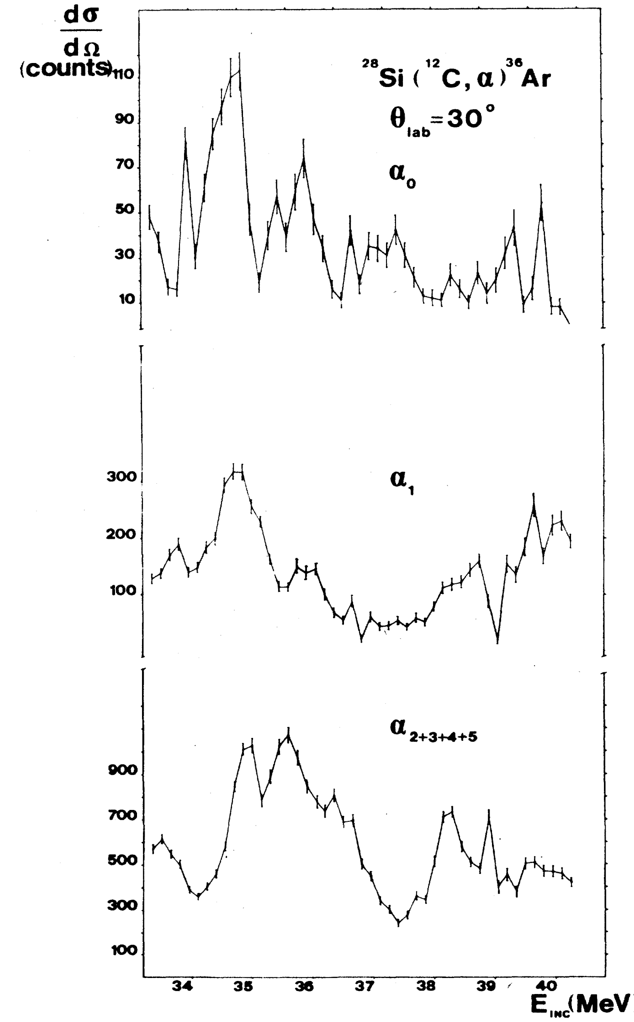

FIG. 1. Excitation functions of the $^{28}Si(^{12}C,\alpha)$ reaction at $\theta_{lab} = 30°$.

smaller indeed, even smaller than the energy step ΔE used to construct the excitation functions, and also smaller than the entrance channel energy resolution. It is well known that in such cases the autocorrelation function analysis does not give reliable results. We therefore reanalyzed the α_0 excitation function using the method of the fluctuation amplitude reduction. This method, known as the Gibbs's method, was worked out in the 1960's to analyze cases, like the one being studied here, in

TABLE I. Results obtained from the fluctuation analysis of the $^{28}Si(^{12}C,\alpha)$ excitation functions. The fourth column shows the mean-square deviation coefficients, the fifth column the Γ values extracted by means of the autocorrelation function; the same values corrected for the finite range of data effect (Ref. 7) are shown in the sixth column. The errors are $\approx 20\%$ for α_1 and α_{2-5}, $\approx 40\%$ for α_0.

Group	Excitation energy (MeV)	J^π	C (O)	Γ (keV)	Γ_{corr} (keV)
α_0	0	0^+	0.406	50	50
α_1	1.97	2^+	0.257	350	440
$\alpha_{2+3+4+5}$	4.18-4.33-4.41-4.44	$3^-,4^+,2^+$	0.149	380	490

which the energy resolution is larger than the correlation width, and has been fully described in Ref. 7. The result for α_0 was $\Gamma = 50 \pm 20$ keV.

We then proceeded to evaluate the widths expected for the ^{40}Ca compound nucleus at an average excitation energy of ≈ 38 MeV. As a first approach, we referred to the experimental result of ≈ 10 keV reported in Ref. 6 (included in the systematics of Ref. 7) for the ^{40}Ca compound nucleus formed by means of a $^{39}K(p,\alpha)$ reaction at 19 MeV excitation energy. Using the well-known exponential dependence of the CN width with excitation energy and the parametrization of Stokstad,[8]

$$\Gamma = 14 \exp[-4.69(A/E^*)^{1/2}] , \tag{3.1}$$

we can extrapolate the above-mentioned result to 38 MeV obtaining $\Gamma \cong 73$ keV. An explicit calculation was also performed with the Hauser-Feshbach theory by using the program STATIS of Stokstad.[9] The result was 45 keV. We should like to observe that the width obtained for α_0 is fully consistent with the previous results, while the widths obtained for the other two groups are 1 order of magnitude larger. While an interpretation of the measured structures in terms of isolated resonances could be ruled out by considering the lack of correlation among different channels (values for the fractional cross-correlation coefficients range from 0.06 to 0.2), we proceeded to check whether interpretation in terms of the doorway-state fluctuations proposed in previous work would be compatible with the present results. To do this, we first had to verify the presence of intermediate processes of the multistep compound type of our reaction. We therefore calculated the spectrum shape of the ^{28}Si(^{12}C,α) reaction with the SMCE theory, under the same hypothesis described in Ref. 4. Figure 3 gives the results for different choices of the initial number of degrees of freedom n_0 compared with a typical spectrum, the one at 35.15 MeV. It is clear from this comparison that the data are well fitted by a multistep compound process, presumably initiated by an $n_0 = 5$ configuration, whose last stage is the equilibrium compound nucleus state (r stage). On the other hand, the evaporation contribution itself has a spectral shape much steeper than the experiment, a well-known feature of preequilibrium reactions. Moreover, the depletion factor for the r stage calculated according to Eq. (2.1) of Ref. 5 turns out to be from 0.19 to 0.26 depending on the particular partial wave, therefore implying that only $\approx 20\%$ of the incident flux is available for CN formation. It should be stressed that these findings apply to the entire incident energy range being studied.

With this information, we next calculated the multistep compound width Γ_5 for the ^{12}C+^{28}Si system at 38 MeV excitation energy, by using Eqs. (5.14) and (5.27) (and related ones) of Ref. 5. Following the improvements worked out in the application of the theory and described in Ref. 10, we used harmonic oscillator wave functions to describe the bound states and optical-model functions to describe the continuum states; moreover, level densities were restricted to include only bound configurations according to the cutoff technique discussed in Refs. 10 and 11.

The result was 480 keV, in very good agreement with the values extracted for the α_1 and α_{2-5} groups. As in previous cases, we can therefore conclude that the

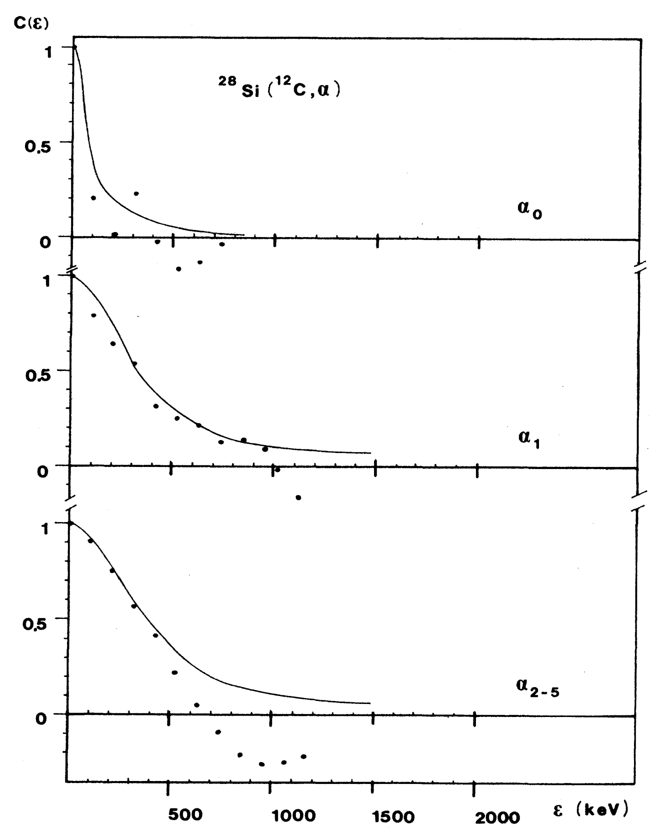

FIG. 2. Relative autocorrelation function analysis of the measured α transitions for the ^{28}Si(^{12}C,α) reaction.

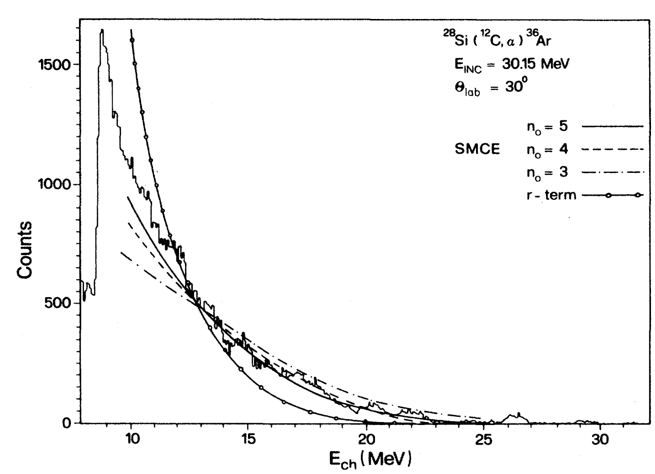

FIG. 3. Experimental spectrum compared with SMCE calculations with different initial number of degrees of freedom n_0 and with the equilibrium r term. For ease of comparison, the theoretical curves are all normalized at 13 MeV.

"large-width" effect can be interpreted as being due to the overlapping of doorway states (in this case 5-exciton-type states) formed in the intermediate system before its fusion. The presence of widths typical of the two processes in the excitation functions of different levels of the residual nucleus is therefore possible, in connection with the degree of their overlap with the different n-exciton states. This result has been theoretically justified in Ref. 12. In particular, in the case of the ^{28}Si(^{12}C,α) reaction, emission from the CN state is important for transition to the g.s. of ^{36}Ar, while emission from an $n=5$ state is dominant in the case of α_1 and α_{2-5} levels. We would also like to point out that the $n_0=5$ (3p,2h) result we obtained for incident carbon ions is clearly consistent with the interpretation in terms of α-particle doorway states which was given in Ref. 4 to $n_0=6$ (4p,2h), obtained for oxygen ions.

IV. ENERGY AND MASS DEPENDENCE OF THE LONG-RANGE CORRELATION WIDTHS

This section presents some already published results on light heavy-ion-induced reactions with as large as possible a range of energy and mass number and compares them with the theoretical behavior predicted by CN and SMCE theories.

The criteria we will use to choose the experimental results appropriate for such a purpose from the vast literature on measurements of excitation functions were the following:

(i) the absence or insufficient correlation of the measured structures among different channels and/or emission angles, which rules out interpretation in terms of isolated resonances;

(ii) a width extracted from the fluctuation analysis significantly larger than the one predicted by CN theory.

The cases to which these criteria definitely apply are listed in Table II together with the cases we have discussed in previous papers.[4,13]

The mass number range was between 27 and 40 and the composite system excitation energy was between 27 and 50 MeV. In all cases except the ^{16}O(^{16}O,^{16}O) reaction discussed in Ref. 14 in terms of doorway-state fluctuations, no convincing interpretation was given for the measured structures, and the difficulty or impossibility of interpreting them in terms of the traditional mechanisms was always confirmed. Table II also gives the correlation widths extracted by means of statistical analysis (autocorrelation function or, in the case of Ref. 14, the spectral density method) by the authors themselves, whenever they had done it, or by us in all other cases (cases 2 and 5).

It has been shown in previous papers that a multiclass fluctuation analysis of an excitation function, performed with the spectral density method, allows extraction of the widths of the dominating classes of states that are being populated (usually two, the first doorway state and the equilibrium CN state), provided that the energy step is at least not too much larger than the smallest width present. This is true of reactions 1, 3, 5, and 8, for which two Γ values were extracted with this method. All the Γ values reported were corrected for the finite range of data effect.[7] In order to understand the energy and mass-number dependence of the widths in Table II, we plotted them in Fig. 4 as a function of $(A/E^*)^{1/2}$. The straight line corresponding to the CN behavior given by STATIS (Ref. 9) was also drawn in Fig. 4.

It is clear that the "small" Γ values, whenever extracted, fall well on this line. On the other hand, the "large" Γ values (Γ_1 in Table II) (1) are well above the CN straight line; (2) do not exhibit any dependence on A,E of the CN type.

If we now go back to our interpretation of the Γ_1 values outlined in Sec. III, we can easily figure out which dependence on A,E is theoretically predicted for such "large" widths.

In the framework of the SMCE theory, the total n-exciton width Γ_n is given by

$$\Gamma_n=\Gamma_n^{\downarrow}+\Gamma_n^{\uparrow}\ , \qquad (4.1)$$

where $\Gamma_n^{\downarrow}$, which describes the intranuclear cascade process, is the dominating term.[5] We therefore calculated $\Gamma_n^{\downarrow}$ for $n=5$, a typical initial configuration for light heavy-ion reactions, for the ^{28}Si composite system at an excitation energy varying from 27 to 37 MeV. The results are shown in Fig. 5. The dependence is linear, and therefore quite different from the exponential behavior typical of the CN width. We should like to point out, incidentally, that the same linear dependence is obtained from the preequilibrium exciton model, the semiclassical ancestor of the SMCE theory. In fact, in this model the intranuclear decay rate $\lambda^{\downarrow}$ is given by[20]

$$\lambda^{\downarrow}=\frac{2\pi}{\hbar}M^2\frac{g^3E^2}{n+1}\ , \qquad (4.2)$$

TABLE II. Γ values for the light heavy-ion reaction discussed in Sec. IV. The numbers shown in the first column are the same as in Figs. 4 and 6.

Case	Reaction	A	E^* (MeV)	Γ_1 (keV)	Γ_2 (keV)	Ref.
1	^{12}C(^{24}Mg,^{12}C)	36	50	505	140	15
2	^{12}C(^{19}F,α)	31	41	375		16
3	^{12}C(^{15}N,α)	27	30	216	70	17
4	^{12}C(^{16}O,α)	28	31	215		4
5	^{28}Si(^{12}C,^{12}C)	40	43	537	58	18
6	^{24}Mg(^{12}C,α)	36	37	353		19
7	^{28}Si(^{12}C,α)	40	37	470	50	Present work
8	^{16}(^{16}O,^{16}O)	32	27	235	25	14

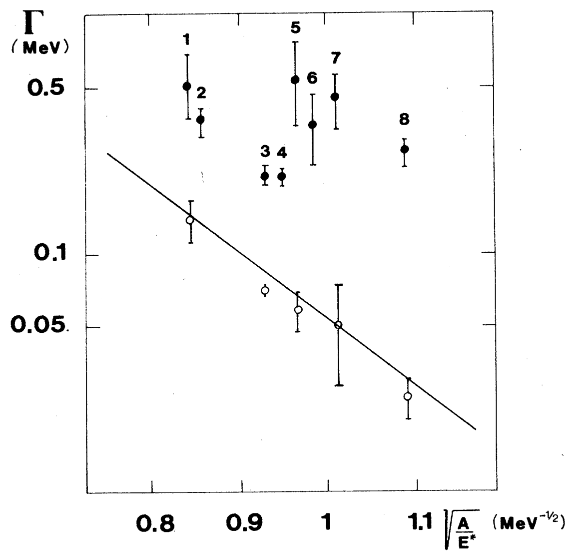

FIG. 4. Γ values for the reactions discussed in Sec. IV vs $(A/E^*)^{1/2}$. The solid and open circles represent the Γ_1 and Γ_2 values of Table I, respectively. The numbers are the same as in Table I. The straight line represents the CN behavior given by STATIS (Ref. 9).

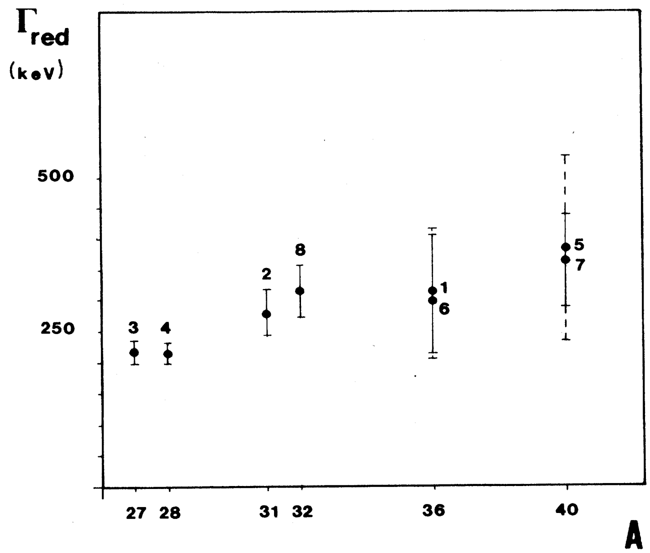

FIG. 6. Γ values divided by the composite system excitation energy for the reactions discussed in Sec. IV vs mass number. The numbers are the same as in Table II.

where the square of the matrix element M^2 is

$$M^2=K/(A^3E)\ , \qquad (4.3)$$

which gives $\lambda \propto E$. Moreover, considering that $g \propto A$, we obtain an A-independent decay rate, once again in strong contrast to the CN results.

In order to better separate the two effects, we eliminated the energy dependence of the Γ_1 widths by dividing them by the appropriate excitation energies normalized to 31 MeV. These "reduced" values $\Gamma_{\rm red}$ were then plotted as a function of A in Fig. 6.

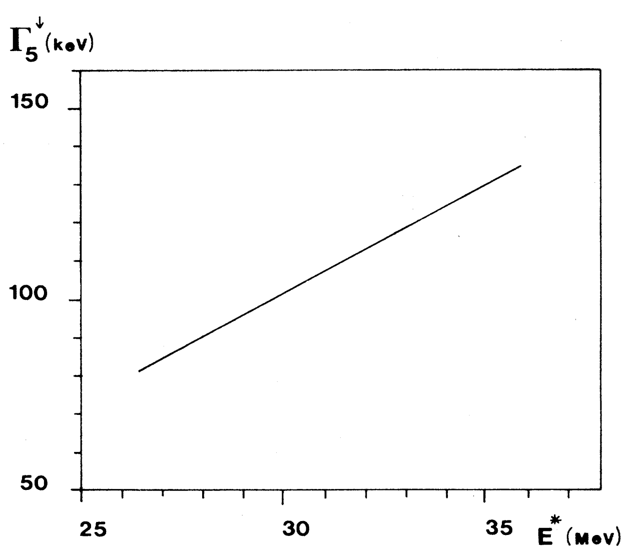

FIG. 5. Dependence of the damping width with composite system excitation energy according to SMCE calculations. The system is ^{28}Si.

The predicted independence from A was verified in a first approximation; the slight tendency towards increasing with A might be due to having approximated Γ with $\Gamma^{\downarrow}$.

V. CONCLUSIONS

In addition to what we have pointed out in previous work and to the remarks made in the Introduction, in this paper we have essentially demonstrated the following.

(1) The measured fluctuations give rise to coherence widths that not only are much larger than the CN widths but have a very different mass and energy dependence.

(2) This dependence (in addition to the value of the width itself) is consistent with the predictions of the multistep compound theory of preequilibrium reactions.

(3) Such a different dependence may be used to discriminate clearly between the CN and the doorway-state widths (their ratio being as large as 10 for a relatively heavy system such as the $A=40$ system measured in this paper).

To summarize, an important result of this paper and of the entire connected project is that the discrepancies often found in interpreting the fluctuations of light heavy-ion reactions in terms of a pure CN mechanism do not necessarily imply the presence of nonstatistical isolated resonances. This is particularly true in all the cases, such as the ones mentioned in Sec. IV, in which no clear correlation can be seen among the structures at different angles and/or channels.

We have definitely shown that a third process might be present, which would resolve these difficulties. Indeed, no correlation is necessary in this case because such a process is statistical exactly like the CN process; on the other hand, it predicts larger correlation widths, which is precisely what is observed in these "difficult" cases. These widths correspond to lifetimes of the order of 10^{-21} s, clearly intermediate between the CN lifetimes (10^{-20} s) and the nuclear transit time (10^{-22} s).

As far as the nature of such an intermediate process is concerned, during this project we have presented evidence in favor of the SMCE mechanism because: (1) it verifies the condition $\Gamma_n > D_n$ necessary for the existence of fluctuations; (2) it reproduces the spectrum shape of the emitted particles; (3) it reproduces the measured values of the "large" correlation widths; and (4) last, but not least, it gives the correct energy and mass-number dependence of such widths.

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