Multistep compound processes in heavy-ion-induced reactions

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We suggest the possible contribution of multistep compound processes to light heavy-ion reactions at above-barrier energies. The presence of several correlation widths that characterize the fluctuation in energy of the excitation functions for different incident-outgoing channel combinations is indicated and demonstrated explicitly for the system $^{12}C(^{15}N, \alpha)$ at $E_{c.m.}=9.51-17.33$ MeV. The importance of multistep compound processes to heavy-ion fusion studies is pointed out.

[NUCLEAR REACTIONS Multistep compound processes in heavy ion reactions discussed.]

Recently,[1] it was recognized that, even in the absence of direct reactions, the conventional Hauser-Feshbach theory has to be modified to account correctly for the spectra of outgoing particles in light-particle induced reactions [e.g., $^{27}Al(^{3}He,p)$]. These spectra exhibited rather significant deviations from the usual Hauser-Feshbach evaporation forms. The deviations were, however, convincingly accounted for by the recently developed theory of statistical multistep compound emission (SMCE).[2] Further evidence was obtained from fluctuation analysis made on the same system studied in (Ref. 1), that resulted in two correlation widths which may be assigned to the two, presumably dominant, steps through which the system $^{27}Al+{}^{3}He$, at $E_{lab}=9-14$ MeV develops.[3] The fluctuation analysis carried out in Ref. 3 was based on the generalized cross-section autocorrelation function, appropriate for multistep (or multiclass) compound reactions, that has been derived recently[4] within the "nested doorway" model.[5]

It is the purpose of this paper to present evidence for the occurrence of multistep compound processes in heavy-ion induced reactions. We base our analysis on already published data.

Among the most conspicuous differences between light and heavy-ion induced reactions is the rather clear separation, in the latter, between the coherent, direct processes and the statistical, compound ones. This separation comes about in heavy ions, in part, as a result of the greater geometrical extension of the system on the one hand and, on the other hand, the rather "windowlike" nature of direct processes that makes them confined to the surface region. Such a separation has the virtue of simplifying the analysis of heavy-ion compound reactions even in a case where competition from direct processes is strong. In contrast, light-ion compound reactions, under similar conditions, require quite an intricate modification of the Hauser-Feshbach theory.[6] Another important difference between light-ion and heavy-ion reactions is the greater number of excitons, in the latter, that characterizes the first class of overlapping resonances ("doorways") which are populated. In a nucleon induced reaction, on the other hand, the first class of doorways populated is usually characterized by three-exciton configurations.

We believe that a careful sorting out of the different classes of overlapping doorways through which the heavy ion system passes before eventually reaching the equilibrated compound stage, could shed light on the fundamental mechanism that underlies the fusion of heavy ions.[7] Careful fluctuations analysis may do exactly this sorting. Drawing from experience in light particle reactions, one may associate the greater-valued correlation width with the first class of overlapping doorways populated from the entrance channel, and the smallest of all correlation widths, called Γ_r in Ref. 2 and Γ_N in Ref. 4, with the equilibrated compound nucleus. This compound nucleus correlation width is found empirically to depend on the mass number A of the compound system, and the corresponding excitation energy E_x, as[8]

$$\Gamma_N = 14\exp[-4.69\sqrt{A/E_x}](\text{MeV}) . \quad (1)$$

In what follows we corroborate on the above arguments.

A rather large fraction of the literature on light heavy-ion compound reactions deals with attempts to observe intermediate structure-isolated resonances (quasimolecular resonances).[9] Although in several cases, e.g., $^{12}C+^{12}C$ and $^{12}C+^{16}O$, the evidence for these resonances is rather convincing, in many instances, however, these attempts are plagued with several difficulties.[10] An important first step in analyzing the experimental excitation functions in quasimolecular studies involves a careful extraction of the background usually associated with statistical (Ericson) fluctuations which are characterized by a correlation width given approximately by Eq. (1). We have found that in several of the publications listed in Ref. 10 the range of values of the extracted correlation width is much wider than allowed by Eq. (1), even if refinements are introduced to account for spin dependence, etc. These discrepancies are characteristically attributed to "anomalies," which are then completely discarded by taking the average of all the Γ_N values, which then results in a quite large standard deviation. No convincing arguments were given as to why these discrepancies should not be physically relevant. Indeed, the analysis of the reaction $^{10}B(^{16}O,\alpha)^{22}Na$ studied in the energy range $E_{\text{c.m.}} = 15.4-17.7$ MeV [Ref. 11(a)] gave values for Γ_N ranging between 45.6 and 648 keV, with several centered at ~ 300 keV. Similarly, the reaction $^{12}C(^{16}O,\alpha)$ at $E_{\text{c.m.}} = 17.1-19.7$ MeV [Ref. 11(b)] gave rise to values of Γ_N in the range 60 keV $\leq \Gamma_N \leq 300$ keV.

We believe that such a wide range of values of Γ_N obtained in the above studies stems from their using Ericson's original, one-class formula for the cross section autocorrelation function which, in the absence of direct reactions, has the form[12]

$$C_{ab}(\epsilon) = \left| \frac{\sigma_{ab}}{1+i\epsilon/\Gamma_N} \right|^2 , \quad (2)$$

where σ_{ab} is the average fluctuation cross section. Indeed, the recent analysis of the reaction $^{27}Al(^3He,p)$ (Ref. 1), has convincingly demonstrated the above mentioned difficulty that is encountered when using Eq. (2). The same data were subsequently reanalyzed[3] with the generalized cross section autocorrelation function of Friedman *et al.*[4]

$$C_{ab}(\epsilon) = \left| \sum_{n=1}^{N} \frac{\sigma_{n,ab}}{1+i\epsilon/\Gamma_n} \right|^2 , \quad (3)$$

where n labels the different classes of overlapping doorways and $\sigma_{n,ab}$ labels the corresponding fluctuation cross sections.[13] The result of (3) indicated the presence of only two Γ's which have the very simple physical interpretation given earlier. An important point that should be readily recognized in Eq. (3) is that different combinations of incident-outgoing channels (ab) would dictate a different number of steps involved in the reaction, and accordingly a different number N of terms in Eq. (3). [The number of terms in Eq. (3) refers also to the number of correlation widths Γ_N that are to be extracted.] This is so since the complexity of a given channel would also indicate the type of doorway class to which it couples strongly. The terms $\sigma_{n,ab}$ are well defined,[5] and a computer program for calculating them is available.[1]

In order to demonstrate the occurrence of multistep compound processes in heavy-ion induced reactions, we have considered the data on $^{15}N(^{12}C,\alpha)^{23}Na$ in the range of energies $E_{\text{c.m.}} = 9.51-17.33$ MeV in steps of 88 keV (in the center of mass), measured by Gomez del Campo *et al.* [Refs. 11(c) and 11(d)]. The authors of Refs. 11(c) and 11(d) have made a careful statistical analysis of the data using Eq. (2) and have obtained several values of Γ_N. We have reanalyzed their data allowing the presence of several distinct Γ_n's guided by Eq. (3). In our analysis we have considered those excitation functions that seem to exhibit pure statistical fluctuations (i.e., with no obviously correlated peaks). The results of our analysis for several excitation functions are summarized in Fig. 1. As one can clearly see, the autocorrelation function for the transition to the ground state ($\frac{3}{2}^+$) in ^{23}Na, shown in Fig. 1(a), exhibits two correlation widths: $\Gamma_1 = 400$ keV and $\Gamma_N = 70$ keV. The fit obtained with Eq. (3) also gave $\sigma_1 = 0.65$ and $\sigma_N = 0.35$. What is quite interesting is that with the same values for Γ_1 and Γ_N as given above, but with different σ_1 and σ_N, we were able to obtain the fits to the autocorrelation function for the summed $E^*_{\text{Na}} = 7.180-7.272$

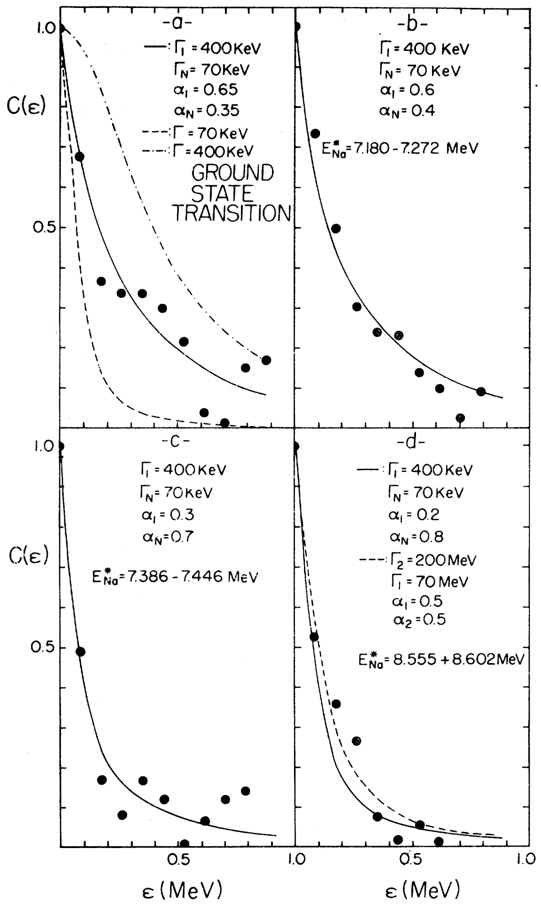

FIG. 1. Autocorrelation functions for four of the excitation functions measured in Ref. 11(c). The fits were obtained with Eq. (3). (a) Ground state transition. Full line was obtained with (3). Dashed and dashed-dotted lines were obtained with Eq. (2) (one class). (b) Summed transitions to states in ^{23}Na with excitation energies in the range 7.180–7.272 MeV. (c) Same as (b) for the range 7.386–7.446 MeV. (d) Same as (b) for the summed transitions to the 8.555–8.602 MeV excited states.

MeV and $E^*_{\mathrm{Na}}=7.386-7.446$ MeV transitions, shown in Figs. 1(b) and 1(c). Figure 1(d) shows a case ($E^*_{\mathrm{Na}}=8.555-8.602$) where presumably the smaller correlation width of 70 keV and another, intermediate one ($\sim$200 keV) seem to play a role. Most of the other excitation functions measured in Ref. 11(b) (28 altogether) were also analyzed and found to exhibit fluctuations with a correlation width that is either 70 or 400 keV and in some cases 200 keV. We interpret the smaller Γ_N value of 70 keV as indicating the lifetime ($\hbar/\Gamma_N$) of the equilibrated compound ^{27}Al nucleus; the larger Γ_1 value of 400 keV represents the simplest of all classes of overlapping doorways (with a corresponding lifetime of $\hbar/\Gamma_1$) to which the incident channel is coupled strongly, and finally $\Gamma_2=200$ keV represent a class of complexity intermediate between that of class 1 and that of N.[14]

In conclusion, we have demonstrated that some of the already published heavy-ion data, particularly those of Ref. 11(c), do contain contributions from multistep compound processes. The extraction of the correlation widths associated with the different stages of the compound nucleus reactions, should be of great help in furthering our understanding of the heavy ion system and could furnish valuable information concerning the mechanism of heavy ion fusion. Recently introduced concepts, e.g., the "statistical yrast line,"[15] introduced to account for the fusion cross section data at higher energies, could very well be connected to the population of the first class of doorways.

The usually discarded "nuclear noise," related to statistical fluctuations in heavy ion resonance studies, may contain as much useful information about the dynamics of the heavy ion system as those extracted from isolated, quasimolecular resonances.

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