Statistical "Doorway" Role of the Dinucleus in Heavy-Ion Deep-Inelastic Reactions

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The statistical role of the dinucleus as a "doorway" in heavy-ion deep-inelastic reactions is discussed. A detailed analysis of the reactions $^{28}Si + ^{64}Ni$ at 120 MeV $< E_{lab} <$ 126.75 MeV and $^{12}C + ^{24}Mg$ at $30 < E_{c.m.} < 42$ MeV is presented. It is pointed out that the lifetime of the dinucleus extracted from excitation-function fluctuation analysis (Ericson fluctuation analysis) is close to that extracted from the final-fragment angular and charge distributions.

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It is by now clear that deep-inelastic heavy-ion reactions are statistical processes that are characterized by a time delay intermediate between direct and compound nuclear reactions. This is evidenced by nonequilibrated exit-channel mass distributions (peaking around the projectile mass), and, on the other hand, by the complete damping of the energy and angular momentum of relative motion. In very heavy-ion systems, one usually employs classical deflection functions to obtain the correlation of energy loss with average deflection angle, through which one extracts the reaction time ($\sim 10^{-21}$ s).[1]

In light heavy-ion systems, the strong Coulomb focusing, commonly seen in heavier systems, is missing. In fact, here one encounters an orbiting-type angular distribution which behaves as $d\sigma/d\Omega \propto 1/\sin\theta$ at larger angles, resembling very much a compound-nucleus angular distribution.[2] This fact is consistent with the idea that a rather long-lived dinucleus is formed in the initial stage of the reaction, which would act as a "doorway" to deep-inelastic collisions (DIC's).

So far, however, evidence in favor of the idea of the dinucleus has been indirect, and only recently were attempts made actually to study the statistical consequences of its presence through a fluctuation analysis[3] of the DIC excitation functions.[4,5] Further, the recent global analysis of heavy-ion fusion reactions done by Hussein *et al.*[6] also clearly indicated the important role of the dinucleus as a "doorway." Therefore one reaches the conclusion that a consistent picture of both DIC's and fusion does emerge if one considers explicitly the dinucleus as a common doorway. At a more microscopic level, one of course would view the dinucleus as a kind of geometrical realization of overlapping, doorway configurations.[6]

In the Ericson fluctuation analysis reported in Refs. 4 and 5, one obtains the average width and the lifetime of these doorway configurations. To what extent is this lifetime identifiable with the lifetime that is usually extracted from the final-fragment charge and angular distribution? It is the aim of this Letter to present a comparison of these lifetimes for the systems studied in Refs. 4 and 5. Further, we attempt to answer the question of how to formulate a theory of hybrid nuclear reactions that leads to fluctuating excitation functions (reminiscent of compound processes) and forward, grazing, peaked angular distribution.

We first consider the reaction $^{28}Si + ^{64}Ni$, in the laboratory energy range 120 MeV $< E_{lab} <$ 126.75 MeV, studied recently by De Rosa *et al.*[4] These authors sured the DIC excitation function, corresponding to a Q-value bin of about 25 MeV. Normally one expects, in such an inclusive measurement, to wash out all statistical Ericson-type fluctuations (since the magnitude of the oscillations goes like N_{eff}^{-1}, with N_{eff} being the effective number of channels expected to couple to the source of these fluctuations). However, if a dinucleus is formed with a lifetime shorter than that of the compound nucleus and acts as a doorway to DIC's, one may see its remnant in the form of overall modulations in the inclusive-cross-section excitation function.

We show in Fig. 1 the extracted dinucleus lifetime, from a fluctuation analysis that employs the spectral density method,[7] for different projectilelike fragment charges ($10 < Z_f < 16$). Also indicated in the figure is the nuclear passage time ($\cong 3.0\times10^{-22}$ s). The compound-nucleus time delay (if it were formed) is about 66.0×10^{-22} s. Therefore the energy fluctuations in the DIC excitation functions correspond to a class of overlapping resonances intermediate in complexity.

The above considerations are concerned with the effect of the dinucleus on the initial (entrance) channel, which manifests itself in the form of statistical energy fluctuations in the DIC excitation functions. Now we turn to the consequences of the formation of the di-

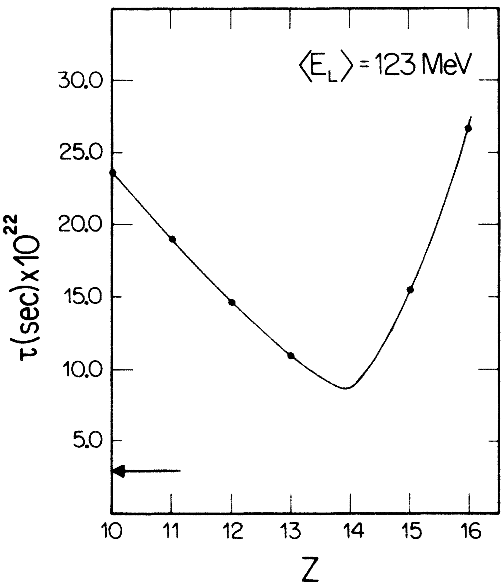

FIG. 1. Dinucleus lifetimes extracted from different fragment-charge channels in the DIC of $^{28}Si + ^{64}Ni$ (Ref. 3). See text for details. The arrow indicates the nuclear passage time.

nucleus on the final-channels charge and angular distributions.

We present in Fig. 2 the measured charge distributions for several center-of-mass angles. The figure shows the usual feature of a gradual broadening of the charge distribution with increasing angle away from the grazing one. In fact, it is easy to verify the diffusion nature of the charge transfer by looking at the variation of the square of the width at half maximum of the charge distributions as a function of angle (or equivalently reaction time). This is shown in Fig. 3. The straight-line behavior clearly indicates the diffusionlike variation of the width versus angle.[1,8] We should mention here that in DIC reactions exhibiting strong focusing, such a behavior is not so apparent.

At this point it is necessary to develop a model which exhibits both statistical fluctuations in the entrance channel and also some kind of focusing in the angular distributions of outgoing fragments. This implies that phases of the S-matrix elements are not completely random; the averages of products such as $\langle S_l^*, S_l\rangle$ are not zero for several values of unequal l and l' (see below).

Several papers have addressed the question of partial coherence (or partial statistical nature) in heavy-ion reactions.[9,10] These authors, however, have looked only at the energy-averaged angular distributions. Here, we attempt to extend the discussion to include also the excitation function and the corresponding cross-section correlation function.

Let us indicate by S_l the partial-wave S-matrix element relevant to our DIC problem. It seems plausible to assume that the energy average of S_l is zero, consistent with the statistical nature of the reaction under consideration. The second moment $\langle S_l^*, S_l\rangle$ of S_l is $\langle S_l^*, S_l\rangle = F(l,l')\exp[i(\delta_l, \delta_{l'})]$ where $F(l,l')$ represents the degree of coherence among the partial waves; namely $F(l,l') \propto \delta_{ll'}$ for entirely incoherent compound processes, while it has a finite distribution in $l - l'$ for the more coherent DIC under consideration.

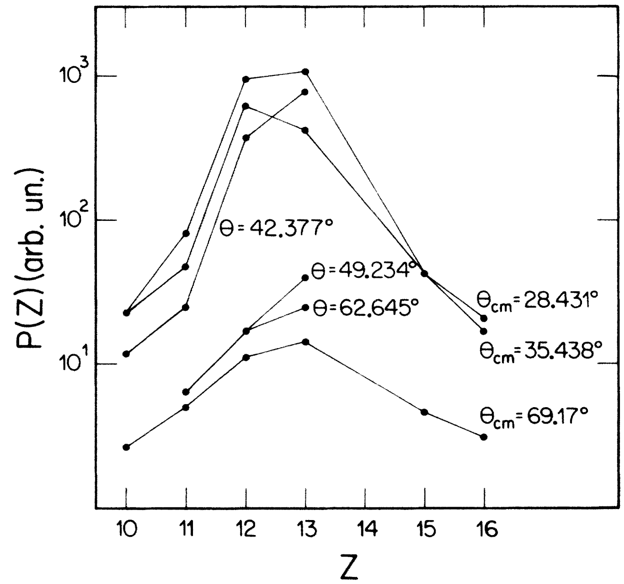

FIG. 2. The measured charge distributions for $^{28}Si + ^{64}Ni$ (Ref. 3) for several center-of-mass angles.

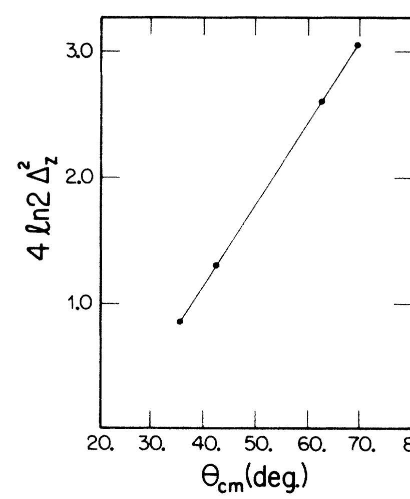

FIG. 3. The square of the width at half maximum of the charge distributions vs the center-of-mass angle for $^{28}Si + ^{64}Ni$.

What interests us here is the S-matrix correlation function defined by

$$C_{l,l'}^{(S)}(\epsilon) = \langle S_{l'}^{*}(E) S_{l}(E+\epsilon)\rangle \quad (1)$$

with which the experimentally measurable cross-section correlation function can be checked. If S is dominated by the dinucleus resonances, these will appear as poles. A possible form for C, which maintains the feature of partial coherence, is

$$C_{l,l'}^{(S)}(\epsilon) = [\langle X\rangle\langle X\rangle/(1+i\epsilon/\Gamma_{\mathrm{corr}})]\exp[-(l-l')^2/2\lambda_c^2]\exp[i(l-l')\langle\theta_{l_0}\rangle], \quad (2)$$

where Γ is the coherence width inversely proportional to the dinucleus lifetime, λ_c is the correlation length which measures the number of interfering partial waves, and $\langle\theta_{l_0}\rangle$ is the average deflection function. The $\langle X\rangle\langle X\rangle$ factor is directly related to the partial cross section.[11] The expression given above results in an average cross-section correlation function which is practically angle independent. Further the average cross section would still present the usual characteristics of angular focusing.

The degree of focusing, and thus the deviation from a pure statistical behavior (symmetry about 90°), of the average cross section can be assessed through a knowledge of the correlation length λ_c. One can establish the following relation[9] between the correlation width of the dinucleus Γ_{corr} and λ_c:

$$\lambda_{\mathrm{corr}} = (2\mathcal{J}_d/\hbar^2c^2\delta)\Gamma_{\mathrm{corr}}, \quad (3)$$

where $\mathcal{J}_d$ is the moment of inertia of the dinucleus,

$$\mathcal{J}_d = \tfrac{2}{5}A_1R_1^2 + \tfrac{2}{5}A_2R_2^2 + \mu(R_1+R_2)^2, \quad (4)$$

and δ measures the angular dispersion of the wave packet describing the system at the moment of contact.[9] It is of the order of a few times $\hbar$ (if measured in these units). Using for the radius parameter the value $r_0 = 1.2$ fm, we obtain for the moment of inertia of the dinucleus in ^{28}Si + ^{64}Ni the value $\mathcal{J}_d = 2.1 \times 10^6$ MeV fm^2. We thus have

$$\lambda_{\mathrm{corr}} \simeq (102/\delta)\Gamma_{\mathrm{corr}} \simeq (10\ \mathrm{MeV}^{-1})\Gamma_{\mathrm{corr}}. \quad (5)$$

For the range of values of Γ_{corr} reported by De Rosa,[4] namely 200 keV $< \Gamma_{\mathrm{corr}} <$ 800 keV, shown in Fig. 1 as h/Γ_{corr}, we obtain the corresponding range of values of λ_{corr}, $2 < \lambda_{\mathrm{corr}} < 8$. Thus the number of interfering partial waves range between 2, for fragment charge several units away from the projectile, and 8 for projectilelike fragments. This is quite consistent with the measured angular distributions of these fragments: grazing-angle peaked for projectilelike fragments indicative of a rather strong focusing resulting from a larger number of interfering partial waves, compared to a very broad distribution for other fragments.

For the lighter systems, such as the one studied by Glaesner *et al.*[5] (^{12}C + ^{24}Mg), we obtain $\mathcal{J}_d = 2.0 \times 10^5$ MeV fm^2, which gives

$$\lambda_{\mathrm{corr}} = (9.63/\delta)\Gamma_{\mathrm{corr}} \simeq \Gamma_{\mathrm{corr}}/(1\ \mathrm{MeV}); \quad (6)$$

with the Γ_{corr} value obtained in Ref. 4, namely 0.24 MeV, we get $\lambda_{\mathrm{corr}} < 1$. This is clearly consistent with the type of angular distribution of DIC products reported by Glaesner *et al.*,[5] namely completely isotropic resembling very much a process occurring via the compound nucleus.

In conclusion, we have shown that the time delay of deeply inelastic reactions extracted from final-fragment distributions (angle, charge, etc.) is consistent with that deduced from the entrance-channel energy fluctuations. This clearly demonstrates the "doorway" role of the dinucleus formed in the initial stage of the reaction. A simple relation between the number of interfering partial waves, exemplified by the correlation length λ_{corr}, and the correlation width Γ_{corr} extracted from Ericson analysis of DIC excitation function has been established.

It would be extremely interesting to extend these findings to very heavy systems through detailed measurements of the energy dependence of the DIC cross section.

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