Role of the number of open channels in the dynamics of the dinucleus binary decay

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The occurrence of orbiting and fusion-fission processes observed experimentally in some light and medium-light heavy-ion collisions at incident energies well above the Coulomb barrier is discussed in the framework of a number of available open channels calculation. The fusion-fission mechanism appears to be less competitive in systems for which the available phase space for the highest partial waves is restricted to a few exit channels where dinuclear configurations can survive through orbiting trajectories. The coexistence of quasimolecular resonances, orbiting mechanisms, and the fusion-fission process for medium-light dinuclei is also briefly discussed.

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I. INTRODUCTION

It has been recently well established [1–7] that in a large body of available experimental data on fully energy-damped fragments produced in medium-light nuclear systems (in the $40 \leq A \leq 60$ mass region), the fusion-fission (FF) process has to be taken into account when exploring the limitations of the complete fusion (CF) process at large angular momenta. The competition and the differences between the FF [1–7], orbiting [8–15], and heavy-ion resonance [16–20] reaction mechanisms, all occurring for the near-grazing partial waves, are still currently under investigation and a global understanding of the properties of these phenomena is needed. At energies close to the Coulomb barrier the incoming angular momenta are low enough that light particles (n, p, and α) evaporated from the compound system can easily carry away these angular momenta. However, for higher bombarding energies, the grazing angular momentum increases at a faster rate than it can be dissipated by evaporation of light particles. The fusion-evaporation decay of the formed compound nucleus (CN) becomes less and less effective for the near-grazing partial waves and the dinucleus is progressively forced to proceed prior to fusion through binary reactions such as quasielastic and deep inelastic scatterings or FF channels after fusion. The yields from these different channels come from a very interesting region of the reaction phase space, as they result from more peripheral collisions with eventually significant energy and angular momentum dampings. The CF cross sections, corresponding to the lowest partial waves of the head-on collisions, show the bending or the saturation in the excitation functions which is observed in the experimental CF data at high incident energies [21]. This general behavior is well described in terms of entrance channel effects by the assumption of the critical distance [22] or in terms of a CN limitation itself by the assumption of the statistical yrast line [23]. In this CF saturation region where a substantial fraction of the incident flux breaks up into two massive fragments, quasimolecular resonances have been found to coexist in some specific reaction channels [16–20]. The concept of a "molecular resonance region," with small CN level density, efficient in selected light heavy-ion systems and linked to their weak absorption, as first shown by the Frankfurt group [24], has been also successfully discussed in the framework of the number of open channels (NOC) calculations [25,26]. This model offered a systematic understanding for the existence of surface transparency and for the observation of resonances among various combinations of light heavy ions. Deep inelastic orbiting mechanisms in more massive systems similarly require weak absorption and few available open channels in contrast to the FF process for which the incident flux is much more statistically spread among several exit channels [3]. Therefore it was found natural to extend the original NOC calculations [25,26] to heavier systems, where both the orbiting process of the dinucleus and the FF of the fully equilibrated CN have been experimentally observed [1–15] in order to give a semiquantitative description and plausible explanations of their basic properties. The calculation method and the results will be presented in Secs. II and III and discussed in Sec. IV in a comparison with available back-angle experimental data.

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II. NUMBER OF OPEN CHANNELS

For the sake of simplicity we consider as open channels only binary reaction channels (including light particles), because three-body reactions are unlikely to occur significantly at energies under consideration. For each system, the NOC is obtained by a triple summation over all possible two-body mass partitions in the exit channels, over all possible angular momentum couplings, and, finally, on all possible energy distributions between the fragments, following the method previously described in Ref. [25]:

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$$N^J(E_{\mathrm{c.m.}}) = \sum_{\substack{A_1+A_2=A_c \\ A_1 \le A_2}} \sum_{J=I_1+I_2+L} \sum_{E_{\mathrm{ex}}=E_1+E_2+Q_{12}+E_r} T_L(E_r) \quad (1)$$

where $E_{\mathrm{c.m.}}$ is the incident c.m. energy and E_{ex} the excitation energy of the compound system. I_1, I_2, and L are the intrinsic spins of the fragments and the orbital angular momentum of their relative motion. Q_{12} is the reaction ground state (g.s.) Q value of the decay into the fragments. E_1 and E_2 are the intrinsic excitation energies of the fragments and E_r the energy available to their relative motion. $T_L(E_r)$ is the transmission coefficient of the outgoing channel as a function of angular momentum and E_r. The transmission coefficients have been calculated using the semiclassical model of the inverted parabolic barrier penetration approximation [27],

$$T_L(E_r) = 1/\{1+\exp[2\pi(E_L - E_r)/\hbar\omega_L]\}, \quad (2)$$

where $E_L = V_L(R_B)$ and

$$\hbar\omega_L = \hbar((1/\mu)\{[d^2V_L(R)/dR^2]_{R=R_B}\})^{1/2} \quad (3)$$

is related to the curvature of the outer barrier. In this expression μ is the reduced mass and $V_L(R)$ is the total real potential including the Coulomb potential, the centrifugal force, and the attractive nuclear potential $V_N(R)$:

$$V_L(R) = V_N(R) + V_{\mathrm{Coul}}(R) + \hbar^2 L(L+1)/2\mu R^2. \quad (4)$$

Instead of the previously used Woods-Saxon form [25], the macroscopic proximity potential of Błocki *et al.* [28] has been chosen as the attractive potential. The Błocki Coulomb potential is taken from [29]. The value R_B is given by the condition $[dV_L(R)/dR]_{R=R_B} = 0$ by using the Wilcke *et al.* parametrization [30] of the barrier height in order to reduce the ambiguities of the E_L and $\hbar\omega_L$ quantities which depend on the potential parameters. A discussion of the initial calculations using the Woods-Saxon nuclear potential and the empirical parametrization of the barrier top proposed by Wilczynski [31] can be found in Ref. [25]. The results of both calculations can be compared for the $^{12}C+^{12}C$ reaction in Fig. 1. Actually in the present calculations, following the study of Ref. [25], a constant $\hbar\omega_L = 0.5$ MeV value not depending upon the system or the angular momentum [3] has been reasonably assumed.

In the summation over energy distributions in expression (1), we use the known discrete energy levels of the fragments recently compiled in the literature [32,33], while for high excitation energies we adopt a shifted and angular-momentum-dependent level density expression with parameters proposed by Gadioli and Zetta [34] from their systematic study of level densities in light nuclei with $A < 70$:

$$\rho(I,E) = \frac{\hbar^3}{12\sqrt{8}}(2I+1)\exp\frac{[-I(I+1)]}{2\sigma^2} \times \frac{\sqrt{a}}{\mathcal{J}^{3/2}}\frac{\exp[2\sqrt{aU}]}{(U+t)^2}, \quad (5)$$

where

$$\begin{aligned} U &= at^2 - t = E - \delta + 70/A, \\ \sigma^2 &= \frac{\mathcal{F}}{\hbar^2}\sqrt{\frac{U+t}{a}}, \\ \mathcal{J} &= 0.7\mathcal{J}_{\mathrm{rigid}}, \quad \mathcal{J}_{\mathrm{rigid}} = \tfrac{2}{5}MR^2\mathcal{J}, \\ R &= 1.5A^{1/3}, \quad a = A/8. \end{aligned} \quad (6)$$

The gap energies δ are those taken from Gilbert and Cameron [35]. Otherwise, the empirical value $12/\sqrt{A}$ given by Bohr and Mottelson [36] is used. The expression (1) is similar to the Hauser-Feshbach formalism for the compound nucleus but the originality of the present calculations is that direct reaction channels, for example nucleon or alpha-transfer channels with both fragments excited, are explicitly introduced in the determination of the NOC in addition to evaporation channels. The reaction Q values are given by the newly released tables of Wapstra and co-workers [37]. We are interested in the largest possible angular momentum brought in by the incident particle at each bombarding energy, whereas the Hauser-Feshbach calculation is limited to smaller angular

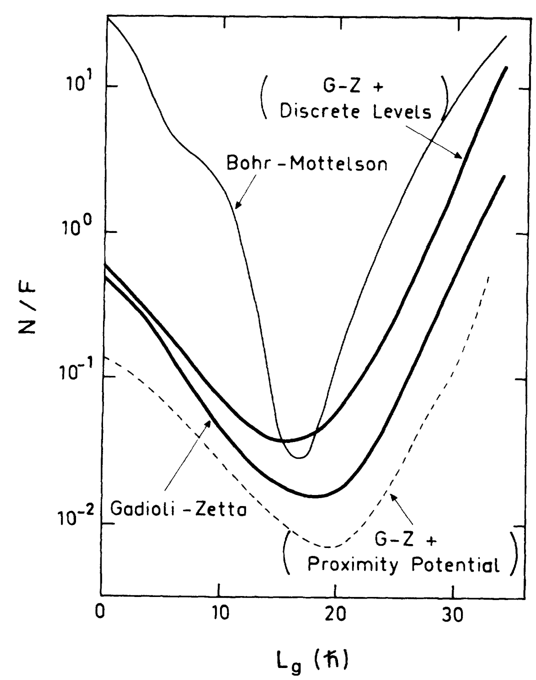

FIG. 1. Dependences of the $^{12}C+^{12}C$ NOC values on the level density formula are dispayed for the Gadioli-Zetta (solid curves) and for the Bohr-Mottelson (fine curve) formulas. The dashed line corresponds to the Gadioli-Zetta NOC calculations using a proximity potential instead of the Woods-Saxon approximation. The NOC's have been normalized to 1 mb of the grazing partial wave flux N/F as discussed in the text.

momenta than the critical angular momentum for fusion $L_{\rm crit}$.

In the following the calculated NOC's available to carry away the incident flux of the grazing partial waves will be presented as a function of the corresponding grazing angular momentum (L_g) calculated from the Wilczynski semiclassical formula [31]. For the comparison among various nuclear systems, it is better to consider N^J per unit of the incident flux, which depends also upon the incident energy and the incoming angular momentum. We define thus the NOC as N/F, the number of open channels per mb,

$$N/F = N^J(E_{\rm c.m.})/F^J(E_{\rm c.m.}), \qquad (7)$$

where $F^J(E_{\rm c.m.})$, the incident flux for the total angular momentum J, is given by the usual expression

$$F^J(E_{\rm c.m.}) = \frac{\pi}{k^2} g_J \sum_{J=L+I_1+I_2} T_L(E_{\rm c.m.}), \qquad (8)$$

where $E_{\rm c.m.} = \hbar^2k^2/2\mu$, and $g_J = (2J+1)/[(2I_1+1)(2I_2+1)]$ with the intrinsic spins I_1 and I_2 of the incident particles. In the case of spin-zero particles, N/F is calculated with $J = L_g$ and the parity $(-)^{L_g}$, while in other cases we calculate with the largest possible J values and the parity given by the product of the intrinsic parities and $(-)^{L_g}$.

Before proceeding to a systematic study with comparisons among various systems, some details of the NOC calculations and their sensitivity to the choice of level density formulas will be given for the $^{12}C+^{12}C$ reaction as a typical example. As has been previously mentioned, we have used the known discrete energy levels compiled for each isotope and for the higher excitation region the level density formula (5) with the parameters (6) given by Gadioli and Zetta [34].

Figure 1 shows the NOC values also calculated with Bohr and Mottelson's level density formulas [36] without the compiled discrete levels. Their density formula is

$$\begin{aligned}\rho(E,I) = {}& \frac{2I+1}{24}\sqrt{a}\left(\frac{\hbar^2}{2\mathcal{F}_{\rm rigid}}\right)^{3/2} \\ & \times \left[U - \frac{\hbar^2 I(I+1)}{2\mathcal{F}_{\rm rigid}}\right]^{-2} \\ & \times \exp\left\{2\left[a\left(U - \frac{\hbar^2 I(I+1)}{2\mathcal{F}_{\rm rigid}}\right)\right]^{1/2}\right\}, \qquad (9)\end{aligned}$$

where $U = E - \delta$, $\mathcal{F}_{\rm rigid} = \frac{2}{5}MR^2$, $R = 1.20A^{1/3}$. The gap energies are the same as those in the Gadioli-Zetta formula. The level density parameter $a = A/8$ value appears at present to be rather well established both experimentally [38] and theoretically [39] for the light heavy-ion systems considered in the present study.

The calculations shown in Fig. 1 as full lines have been performed using the simple Woods-Saxon form of the nuclear potential and the Wilczynski approximation of the barrier top. First we can compare the results with the inclusion of discrete levels with those calculated only with the Gadioli-Zetta formula. As a whole they have a very similar dependence on grazing angular momentum to each other. This indicates that the Gadioli-Zetta level densities are able to give a reasonable description even in the low excitation energy region. The Bohr-Mottelson level density formula gives also similar results whether the known discrete levels are included (not shown in the figure) or not. The last NOC curve (shown as a dashed line) is the result of the calculation using the Gadioli-Zetta level density formula along with a proximity potential [28] in the Wilcke *et al.* approximation of the barrier top [30], which is well suited for the heavier nuclear systems under consideration in the following discussion.

The last modification has obviously a small quantitative influence on the NOC, but not on qualitative features which will be considered in the discussion. The most important result in these comparisons is that all the cases have essentially the same characteristic dependence on angular momentum, i.e., they have minima at nearly the same angular momentum with similar NOC values. Thus the results do not essentially depend upon the details of the level density assumptions or upon the choice of the transmission coefficient parametrization. All curves show a characteristic dip at energies well above the Coulomb barrier ($L_g = 0$). The initial drop is due to the increasing difficulty the compound system has in accommodating the largest brought-in angular momenta by the evaporation of light particles alone. As is well known, the CN decays through these channels, but their yields have a tendency to decrease as the spin increases. The subsequent rise occurs when an increasing number of binary channels (such as single and mutual inelastic, nucleon, and alpha transfers, and finally deep inelastic orbiting and FF processes) becomes effectively open. Those binary channels become activated at somewhat higher energies due to their reaction Q values. Thus, before such binary reaction channels, which can carry away large angular momentum, are effectively open, there exists a minimum in the total NOC curve.

In the following, the calculations will be performed using the Gadioli-Zetta level density formula without the inclusion of known discrete levels, and the proximity potential has been chosen in the Wilcke approximation of the barrier top. Preliminary results of this prescription have been reported in Ref. [3] as possible criteria to distinguish between a non-fully-equilibrated dinuclear orbiting composite and the CN that statistically undergoes binary decay through a FF mechanism.

III. RESULTS

The existence of a minimum in the NOC function can be considered to be one of the most general features in the interaction between light heavy ions [25,26]. The discussion of the observation of quasimolecular resonances in terms of the NOC available to carry away the angular momentum brought in by each incident partial wave has been initially proposed by Abe and Haas [25,26] for some lighter heavy-ion collisions ($A \leq 32$). During the last decade, the understanding of the structural aspects of the resonant behavior has been widely investigated and, very recently, extremely unusual configurations of α particles seem to have been discovered by the Argonne group [40] in the ^{24}Mg nucleus through the mutual inelastic ^{12}C(O_2 $^+$)+^{12}C(O_2 $^+$) scattering reaction. Other very striking resonant structures have been discovered in much heavier systems such as ^{24}Mg+^{24}Mg [18] and ^{28}Si+^{28}Si [17] but their underlying reaction mechanism is still under active theoretical investigation [41–48]. Although the observed nonstatistical resonances are commonly assumed to be caused by the formation of a quasimolecule, their structural configurations, in particular at high spins, and those of the corresponding composite systems (^{48}Cr and ^{56}Ni), are not yet well understood. The most compelling evidence for a quasimolecular structure in light nuclei comes from collisions induced by identical α-like nuclei. We therefore have made a systematic study of total NOC for a number of these possible reactions ranging from ^{12}C+^{12}C to ^{32}S+^{32}S. Figure 2 shows the calculated NOC values of most of the α-like nuclei mass-symmetric systems reported as a function of the grazing angular momentum. All NOC curves shown in Fig. 2 present more or less pronounced minima at high grazing spins. The amplitudes of these minima depend strongly on the system and reflect the varying degree of

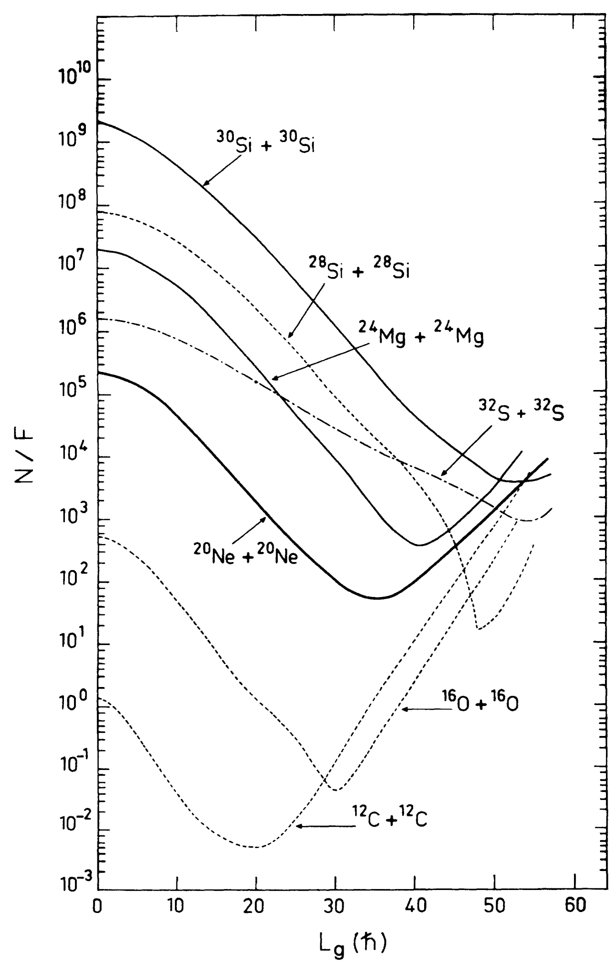

FIG. 2. Calculated NOC values as a function of the grazing angular momenta for the indicated mass-symmetric systems.

transparency of the surface partial waves.

The ^{12}C+^{12}C and ^{16}O+^{16}O systems have strikingly small minimum NOC values and therefore are expected to have enough transparency to allow prominent resonances to show up at high bombarding energies, as shown experimentally in the "pioneering" heavy ions experiments and results of Bromley and collaborators [49,50]. The ^{20}Ne+^{20}Ne system is also a good candidate for resonances to be observed. Although the experimental conditions are difficult, this system is presently under intense investigation [51].

It is interesting to note that the minima of the ^{24}Mg+^{24}Mg and ^{28}Si+^{28}Si reactions are increasingly shifted to higher angular momentum values with a tendency to disappear for the ^{32}S+^{32}S system, which displays no resonancelike features whatsoever [52]. It should be noted, however, that for this system the CN cannot sustain angular momenta larger than 49$\hbar$ according to the modified liquid drop model of Sierk [53]. Actually the two heaviest symmetric systems that exhibit such structure are ^{24}Mg+^{24}Mg [18] and ^{28}Si+^{28}Si [17] (see Fig. 3). For these systems, correlated narrow ($\Gamma_{c.m.}$ = 150–250 keV) structures are observed in the excitation functions for elastic and inelastic scatterings. In Fig. 3 the excitation functions of the large-angle elastic cross sections are shown for the ^{24}Mg+^{24}Mg and ^{28}Si+^{28}Si reactions. The observed intermediate width structures correspond to a complex pattern of isolated resonances in the composite system at high excitation energies with angular momenta, obtained from elastic scattering angular distributions, ranging from 34$\hbar$ to 36$\hbar$ and 36$\hbar$ to 40$\hbar$ for the ^{24}Mg+^{24}Mg [18] and ^{28}Si+^{28}Si [17] reactions, respec-

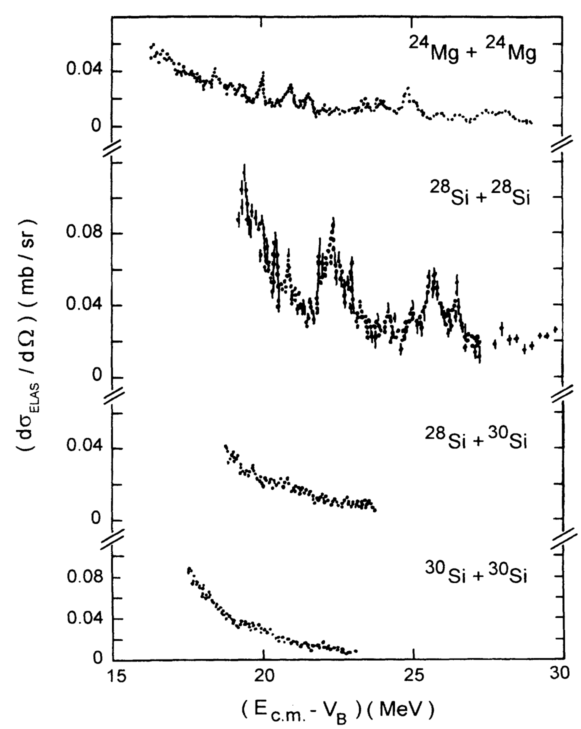

FIG. 3. Experimental angle-averaged large-angle excitation functions for elastic scattering of ^{24}Mg+^{24}Mg [18], ^{28}Si+^{28}Si [17], ^{28}Si+^{30}Si [59], and ^{30}Si+^{30}Si [59].

tively. In fact the angular momenta associated with the resonances are close to and even larger than the grazing values in the entrance channel for such collisions, thus making these resonant states among the highest-spin nuclear excitations lying in the vicinity of NOC minima, a region for which the absorption is predicted to be the least effective.

Although attenuated, similar resonance phenomena have also been observed in the nonsymmetric α-particle system ^{24}Mg+^{28}Si [19] at bombarding energies corresponding to low NOC values, whereas structureless excitation functions [54] have been measured at lower energies outside the "molecular resonance window." This kind of consideration might also be advanced to explain the lack of intermediate width structure in the ^{28}Si+^{32}S reaction [55].

Non-α-like nuclei systems are known to be much less surface transparent [56–58,16], and Fig. 3 nicely illustrates how the addition of neutrons to the colliding ions in the ^{28}Si+^{30}Si and ^{30}Si+^{30}Si reactions [59] damps out the narrow structures which were so prominent in the ^{28}Si+^{28}Si data [17]. It can be observed in Fig. 2 that the ^{30}Si+^{30}Si NOC values are significantly larger than for ^{28}Si+^{28}Si. As a consequence of an increase of the absorption with a pair of added neutrons to the ^{28}Si cores, the total large-angle cross sections have subsequently decreased [59]. This general feature has been systematically evidenced in anomalous large-angle scattering studies [16]. The connection between this backward-angle anomaly, compound elastic and orbiting processes with quasimolecular resonances has been discussed in detail in the literature [8,14,16,17,59]. In particular, the behavior of the large-angle elastic cross sections for the Si+Si collisions, as well as the fully damped fragment mass distribution might also be consistent with the origin of these processes being CN fusion-fission processes [59]. This strong isotopic dependence is in fact rather well correlated with the expected increase of the asymmetric CN fission barrier with increasing N/Z, as discussed in Ref. [59]. The occurrence of a fission mechanism has been further investigated [1] in the ^{16}O+^{40}Ca and ^{16}O+^{44}Ca reactions forming the same CN's as ^{28}Si+^{28}Si and ^{30}Si+^{30}Si, and also in the ^{32}S+^{24}Mg reaction leading to the ^{56}Ni CN [2]. The general features of the observed mass distributions and the fragment total kinetic energies are well reproduced by the statistical transition state model using standard finite-range liquid drop asymmetric fission barriers [4].

Very few experimental results are available for mass-symmetric systems heavier than ^{30}Si+^{30}Si which have quite large NOC values probably preventing observation of resonances. This is the case for the ^{40}Ca+^{40}Ca reaction [60].

Figures 4 and 5 show the calculated NOC values of the ^{12}C and ^{16}O induced reaction systems. From the comparison of the NOC values for these different systems, we would like to emphasize the fact that three kinds of reaction mechanisms might coexist whether the absorption is strong or not.

It has been shown previously (in Fig. 2 for the symmetric ^{12}C+^{12}C and ^{16}O+^{16}O reactions) that the minima are

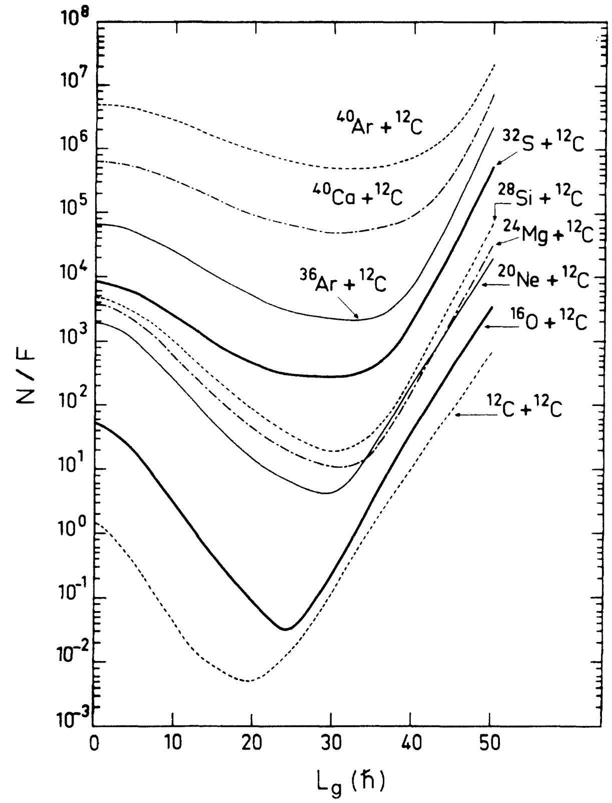

FIG. 4. Calculated NOC values as a function of the grazing angular momenta for the indicated ^{12}C induced reactions.

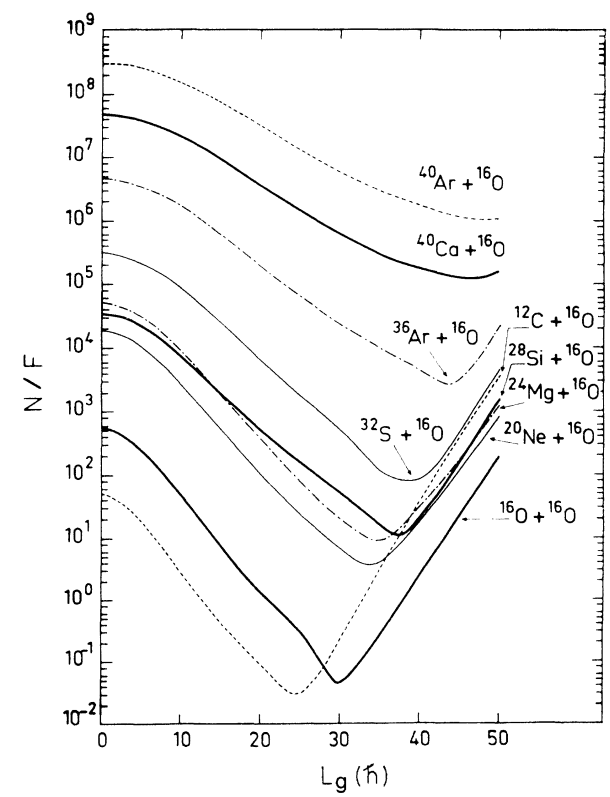

FIG. 5. Calculated NOC values as a function of the grazing angular momenta for the indicated ^{16}O induced reactions.

particularly deep (NOC≅ 10^{-2}–10^{-1}) in the ^{12}C+^{12}C, ^{16}O+^{16}O, and ^{12}C+^{16}O curves and correlated to very prominent resonant behavior, which has been clearly established [49,50,26]. The formation of quasimolecules in these favorable cases needs quite long-time-scale processes requiring a surface-transparent imaginary potential.

The more massive ^{20}Ne+^{12}C, ^{24}Mg+^{12}C, and ^{28}Si+^{12}C systems have larger compound level densities and thus larger spreading width of the entrance channel resonances. However the back-angle elastic scattering of ^{20}Ne [61], ^{24}Mg [61,62], and ^{28}Si [63] ions from ^{12}C display structured excitation functions, shown in Fig. 6, and oscillatory angular distributions in agreement with the relatively weak absorption predicted by the present NOC calculations for these systems. The resonant gross structure for the ^{32}S+^{12}C and ^{40}Ca+^{12}C reactions still remain, but with a disappearance of the intermediate width resonant structure so striking in the ^{24}Mg+^{12}C [62] and ^{28}Si+^{12}C [64] systems. More important is the strong decreasing of the backward-angle elastic scattering yields due to an increasing absorption for heavier systems leading to a larger number of deep inelastic channels and the possible occurrence of the fission process. The strongly damped yields measured for ^{20}Ne+^{12}C [65], ^{24}Mg+^{12}C [14], and ^{28}Si+^{12}C [8] systems show backward-angle rises and follow characteristic $1/\sin(\theta_{\rm c.m.})$ angular distributions in the backward hemisphere consistent with the orbiting picture. As already mentioned, the orbiting processes appear to be strongly connected with the occurrence of reminiscent quasimolecular resonances and will be further discussed in the next section.

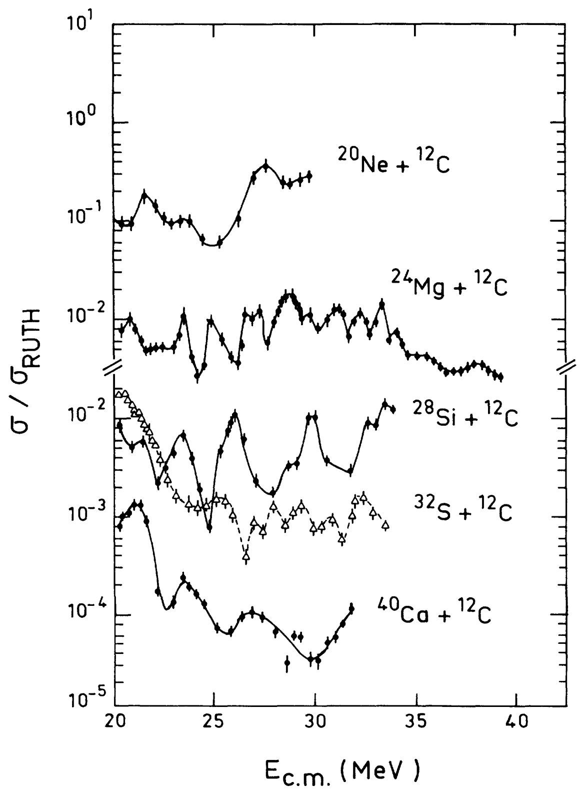

FIG. 6. Experimental backward-angle (near $\theta_{\rm c.m.} = 180°$) excitation functions for elastic scattering of ^{20}Ne+^{12}C [61], ^{24}Mg+^{12}C [61,62], ^{28}Si+^{12}C [63], ^{32}S+^{12}C [58,63], and ^{40}Ca+^{12}C [67].

It can be noticed that the NOC minima displayed in Fig. 4 are smeared out and have much higher NOC values for the ^{32}S+^{12}C, ^{36}Ar+^{12}C, ^{40}Ca+^{12}C, and ^{40}Ar+^{12}C systems; this is consistent with the observed reduction of both the backward-angle scattering yields and the resonant oscillations in elastic excitation functions measured for ^{32}S+^{12}C [58,63,66] and ^{40}Ca+^{12}C [67] (see the ^{32}S+^{12}C and ^{40}Ca+^{12}C experimental data reproduced in Fig. 6). It will be shown that for such collisions the FF process is able to occur as previously found for ^{32}S+^{12}C and ^{40}Ca+^{12}C, for instance [68].

The same observations can be made for the ^{16}O induced reactions for which both the orbiting and FF mechanisms have been experimentally evidenced, depending on the total mass of the composite system; namely, both oscillatory structures and orbiting processes with large cross sections at backward angles have been experimentally observed for the ^{20}Ne+^{16}O [69,70], ^{24}Mg+^{16}O [71,15], and ^{28}Si+^{16}O [16,57,64] collisions. For the heavier ^{40}Ca+^{16}O system [1] the statistical fission has been found to compete favorably, although backward orbiting yields might still persist and compete to some extent with FF [66]. It is interesting to note that nonstatistical fluctuations appear also to show up in the ^{40}Ca+^{16}O reaction [72], with some correlations with ^{28}Si+^{28}Si data [17], as an indication of the possible occurrence of shape isomerism in ^{56}Ni at high spin, predicted by deformed shell model calculations [73]. The shape isomerism in this mass region reflected by the presence of a superdeformed secondary minimum in the nuclear potential energy surface of ^{48}Cr and ^{56}Ni [73] might indeed be responsible for the strong resonant behavior existing in the ^{24}Mg+^{24}Mg [18] and ^{28}Si+^{28}Si [17] reactions. In this alternative explanation, the vanishing of resonances in ^{28}Si+^{30}Si and ^{30}Si+^{30}Si [59] would therefore be explained by the predicted disappearence of these minima in ^{58}Ni and ^{60}Ni. However, the absorption in these collisions is too large for an experimental investigation of such an effect.

IV. DISCUSSION

The present schematic model is capable of giving reasonable predictions of the observations of resonances possibly occurring in light [25,26] and medium-light heavy-ion reactions [3]. Among the various molecular models (see, for example, Refs. [74,75] and references therein), the band-crossing model [76] of Abe and co-workers, the classification of Baye [77], and the orbiting-cluster model of Cindro and Počanič [78] are quite successful to explain the main features of the observed resonances. The orbiting-cluster model has been recently modified to extend the predictions to medium-light heavy-ion systems [79] and particularly to composite systems with closed neutron or proton $g_{9/2}$ shells supposed to present resonant behavior with a high probability. However the excitation function and angular distributions measured for the ^{62}Ni(^{32}S,^{32}S)^{62}Ni reaction are found to be structureless [80], similarly to most of the systems heavier than ^{28}Si+^{28}Si [52,59,60] having a too large NOC for the reaction to be surface transparent.

The observation of intermediate structures and doorway states [81] requires not only the density of levels (spreading width) to be small [78,79] but also a small number of channels (NOC) coupled directly with the entrance channel [25,26,77,82] and linked to the escape width of the resonant doorway state. The main shortcoming of the orbiting-cluster model [78,79] is the neglect of the doorway escape width, which plays an important role in heavier systems with increasing bombarding energies (angular momenta) as evidenced in the present NOC calculations. Depending on the strength of the absorption, which increases with the mass asymmetry and the mass of the composite system, the disappearance of quasimolecular resonant behavior could be interpreted within a global understanding as a gradual transition from deep inelastic orbiting processes, for which entrance channel effects and nuclear structure of the interacting ions play a key role, to the statistical fission mechanism.

The occurrence of the FF mechanism has now been commonly accepted for medium-light dinuclear systems with composite masses $A > 40$ [1–7]. It might even be possible that binary symmetric fission is one of the most probable types of binary decay of the light composite ^{20}Ne system [83]. We have calculated the NOC values for the ^{10}B+^{10}B reaction, which are plotted in Fig. 7 with the results of other light heavy-ion combinations. As compared to heavier systems such as ^{15}N+^{16}O, ^{14}C+^{16}O, or ^{16}O+^{16}O, no marked minimum can be observed for ^{10}B+^{10}B. For ^{10}B+^{10}B, no quasimolecular resonances have been up to now experimentally evidenced [74,75] because for this system NOC values are too large, making this reaction very absorbing as compared to the very surface-transparent ^{16}O+^{16}O case [50,26]. For $L_g > 20\hbar$, the ^{10}B+^{10}B NOC values are larger by at least a factor of 100 as compared to the ^{14}C+^{16}O system, which has been found to show a strong resonant behavior [84]. Since the quasimolecular resonances and orbiting mechanisms appear to be, at least conceptually, very closely connected, one might consider that FF is present for ^{10}B+^{10}B as well as for the ^{10}B+^{18}O reaction, which also presents large NOC values. The FF rather than the orbiting origin of the fully damped yields measured in the ^{10,11}B+^{18}O reactions has been very recently corroborated in Ref. [85], where the most forward center-of-mass angle and nonisotropic binary reaction component corresponds to much faster peripheral mechanisms, in agreement with the deep inelastic orbiting hypothesis [86] for partially energy-damped binary products. Entrance channel effects have been experimentally investigated in the ^{15}N+^{16}O and the ^{12}C+^{19}F reactions leading to the ^{31}P composite system [87]. In agreement with the NOC calculations, the resonant behavior present in the ^{15}N+^{16}O collision [88,89] tends to disappear with the less surface-transparent ^{12}C+^{19}F reaction, similarly to ^{10}B+^{18}O.

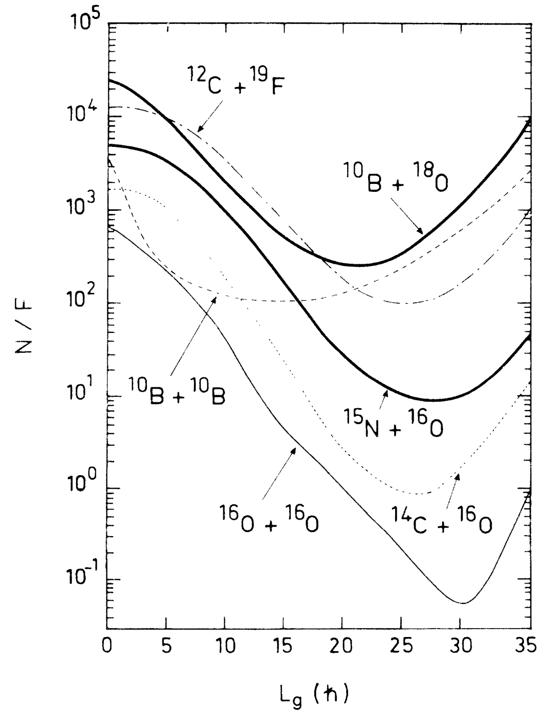

FIG. 7. Calculated NOC values as a function of the grazing angular momenta for the indicated non-alpha-like nuclei systems. The ^{16}O+^{16}O NOC curve is also included for the sake of comparison.

To summarize, although the resonance behavior appears to be a rather common feature in medium-light heavy-ion systems, its observation is restricted to reactions involving α-like nuclei and other closed or almost closed shell nuclei with a small NOC. It has been previously shown by Abe and Haas [25,26] that, although ^{14}C is not an α-like nucleus, the ^{14}C induced reactions have small NOC minimum values (see, for instance, the ^{14}C+^{16}O NOC calculations in Fig. 7). The weak absorption allowed by small NOC's permits the quasimolecular structures to show up experimentally inelastic and quasielastic channels of the ^{12}C+^{14}C [90–92], ^{14}C+^{14}C [92–94], and ^{14}C+^{16}O [84,95] reactions. Similar calculated results have been obtained for the ^{15}N induced reactions, this nucleus having a relatively stable configuration with a closed neutron shell and a high-energy first excited state. The ^{15}N induced reactions on alpha-like nuclei are therefore good candidates to display resonant behavior, as shown in the ^{15}N+^{12}C [96] and ^{15}N+^{16}O [87,88,96] reactions which have been very recently studied. An interesting behavior have been noticed for this kind of resonant reaction, at least for ^{12}C+^{14}C [90] and ^{14}C+^{16}O [84]: the angular momenta involved in the resonances are higher than the grazing values and this corresponds to a dinuclear system where the interacting nuclei orbit each other in a distant collision with a weak superposition of their nuclear densities. The NOC calculations have been performed with the grazing angular momenta (L_g). Calculations using angular momenta larger than L_g would result in an even deeper minimum located at an angular momentum lower than in the normal calculation (see Ref. [84]). This elongated and highly deformed configuration strongly resembles the pole to pole configuration which has been proposed to describe the ^{24}Mg+^{24}Mg resonant structure [18,42,44].

The narrow resonant structures observed in the heaviest α-like systems (^{24}Mg+^{24}Mg [18], ^{24}Mg+^{28}Si [20], ^{28}Si+^{28}Si [17]) are also linked to small NOC values, as shown previously. The resonance cross sections have a strong dependence not only on the mass and charge of the colliding nuclei but also on their nuclear structure and on the mass asymmetry of the entrance channel, as shown for the ^{31}P composite system [87,89]. This last effect is evident for the ^{56}Ni CN which presents the most intense resonant behavior in the ^{28}Si+^{28}Si collision [17]. This resonant structure is apparently more and more damped as the mass asymmetry is increased, as found in the ^{32}S+^{24}Mg [97] and ^{40}Ca+^{16}O [72] reactions. Furthermore, the backward-angle elastic scattering shows a decreasing yield with increasing mass asymmetry in the ^{28}Si+^{28}Si [17], ^{32}S+^{24}Mg [97], and ^{40}Ca+^{16}O [67] reactions due to larger and larger absorption, in agreement with the NOC systematics. It is interesting to note that, in the mass region corresponding to the heavy α-like nuclei collisions [7,18,98,99], both the mass and the energy spectra show a high degree of selectivity probably also due to small NOC values.

The coexistence of the observed resonant behavior and the statistical fission of the ^{48}Cr CN formed in the ^{24}Mg+^{24}Mg collision [7] might be qualitatively explained in the context of the NOC calculations shown in Figs. 2 or 8. The $36\hbar$ ^{24}Mg+^{24}Mg resonance [18] lies inside the "quasimolecular resonance window" which corresponds to the NOC minimum. On the other hand, the angular momenta leading to FF, lower than $30\hbar$, have much higher NOC values and lie in the strong absorption region where the CN is able to undergo binary decay through statistical fission.

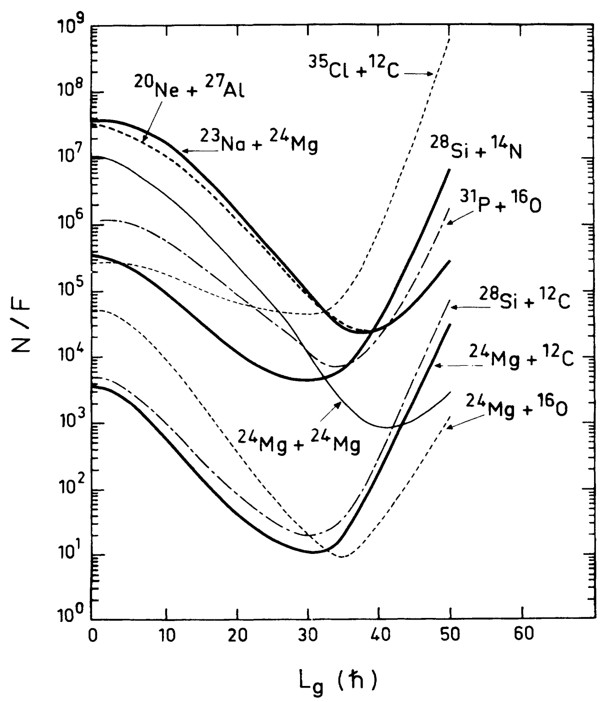

FIG. 8. Calculated NOC values as a function of the grazing angular momenta for the indicated systems.

In Fig. 8, NOC's have been plotted for different nuclear systems for which orbiting processes, quasimolecular resonances, and FF have been experimentally observed. The α-like ^{24}Mg+^{12}C, ^{24}Mg+^{16}O, and ^{28}Si+^{12}C systems have marked NOC minima with NOC values of the order of 10. As already stressed previously and illustrated in Fig. 6, strongly oscillatory angular distributions and highly regular gross structures that occur in the backward-angle elastic scattering of these reactions [14,16,57,61–64,71] might be correlated with the existence of deep inelastic orbiting mechanisms [8,9,13,15]. Superimposed on the gross structures, intermediate width resonances have also been observed [62,64] with large compound nuclear lifetimes. Similar fluctuations occur in more damped processes [14] occurring with orbiting long-lived dinuclei that conserve the entrance channel parentage to a considerable degree until undergoing binary fission. On the other hand, it can be argued that the lack of any significant entrance channel effect and the vanishing orbiting yield in the ^{47}V composite systems [3,5,6] are linked to the fact that the incident flux is expected to be more spread among a larger NOC as compared to tightly bound α-like nuclei collisions forming the ^{36}Ar and ^{40}Ca composites. From Fig. 8 it is clear that NOC's for the ^{47}V systems are much higher than in the ^{40}Ca systems for which the available phase space for the highest partial waves are restricted to a few exit channels where dinuclear configurations can survive through orbiting trajectories. Hence the FF process has been found experimentally competitive in the ^{35}Cl+^{12}C [3,5], ^{31}P+^{16}O [5], ^{23}Na+^{24}Mg [6], and ^{20}Ne+^{27}Al [100,101] reactions, in agreement with the transition state model predictions [4,101]. To our knowledge, unlike the ^{24}Mg+^{12}C, ^{24}Mg+^{16}O, and ^{28}Si+^{12}C reactions, no evidence has been found for the observation of resonant behavior in the ^{28}Si+^{14}N system although orbiting processes are apparently occurring [10]. Actually the calculated ^{28}Si+^{14}N NOC is sufficiently high (see Fig. 8) to prevent the experimental observation of reminiscent resonant structures and to allow more statistical mechanisms to show up to some extent as predicted by recent FF model calculations [4]. These calculations based on the transition state model [4] have been found capable of giving a reasonably good description of the ^{28}Si+^{14}N data [10] while failing to reproduce fully the ^{28}Si+^{12}C orbiting binary yields. A very recent study of alpha induced reaction on ^{27}Al and ^{40}Ca targets [102] indicates a transition from pure orbiting collisions to more statistical processes, in agreement with NOC predictions which imply much larger values for the ^{4}He+^{40}Ca system. This is another confirmation of the importance of a surface-transparent potential in alpha induced reactions [103] as well as in medium-light heavy-ion reactions [16].

In many cases, the origin of experimentally observed fully damped reaction products remains an open problem since different mechanisms could coexist at different stages of the collision; however, it appears that for reactions having large NOC values the FF yield might dominate, whereas for lighter dinuclear systems, composed of rather tight nuclei with smaller NOC values, the orbiting mechanism is favored and quasimolecular resonances are visible at backward angles.

V. SUMMARY AND CONCLUSION

In the present study we have extended to heavier combinations of light heavy ions the initial method of NOC calculation proposed by Abe and Haas [25,26] in order to offer a coherent explanation of the coexistence of quasimolecular resonances and oribiting phenomena observed in surface-transparent dinuclear systems and of the occurrence of more statistical mechanisms such as FF in more absorbing reactions. The details of the calculations and their sensitivity to level densities and transmission coefficients have been discussed extensively. The adopted modified method has been applied for a wide range of dinuclear systems which have been experimentally investigated in the recent past.

It is at present well established that there exists a quasimolecular resonance region at high energies with high spin in the most surface-transparent reactions with small NOC values. The NOC minimum appears to be the stronger for collisions involving α-like nuclei and other closed or almost closed shell nuclei such as ^{14}C or ^{15}N. The predictions for these last collisions have been verified by the experimental observations of resonances. On the other hand, other reactions suffering a stronger absorption do not favor the observations of resonant behavior or orbiting phenomena of the dinucleus. The strong correlation between the anomalous large-angle resonant structures and small NOC is systematically observed in a large number of dinuclear systems, in agreement with the expectations of the present model.

Finally, in those absorbing systems with large NOC values, the deep inelastic orbiting processes have the tendency to vanish to the benefit of the statistical FF of the CN, in agreement with the expectations of the statistical transition state model. In this framework, although controversial, the large phase space available for the binary decay of very light nuclear systems with large NOC values can also support a FF picture for the origin of fully energy-damped fragments.

To conclude, the present model is found to be very useful in order to understand many aspects of dinucleus dynamics, from quasielastic and orbiting processes, with the possible observation of quasimolecular resonances and entrance channel effects, to the formation of the fully equilibrated CN which undergoes binary decay through the statistical FF mechanism. In order to give a further important step forward in describing the dynamics of the dinucleus binary decay, it would be highly desirable to have new precise measurements of the mean interaction times involved in the different reaction mechanisms.

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