Energy dependence of massive-fragment multiplicity

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The production of several massive fragments in the decay of a very excited compound nucleus is studied using simultaneous and sequential mechanisms of fragment production. The calculated massive-fragment multiplicities exhibit remarkably similar behaviors as functions of the excitation energy, thus ruling out using this observable as an experimental signature of the dominant fragmentation mechanism.

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The mechanism for producing massive fragments \((Z > 5)\) in the collision between two heavy nuclei at intermediate beam energies remains uncertain in spite of considerable experimental and theoretical efforts.\(^1\) The number of such massive fragments depends strongly on the bombarding energy. At low energies, \(E/A < 10\) MeV, two such fragments may be produced as a result of fusion-fission or quasifission processes, whereas at high energies \((E/A > 250\) MeV), the massive-fragment yields are well understood on a simple geometrical basis as being the remnants of the spectator portions of the colliding nuclei [1]. In the intermediate energy range the production of several such fragments is common [2], but the underlying mechanisms responsible have not been clearly established yet. Indeed, the question of how a highly excited nuclear source decays forms a central problem in the study of nuclear reactions at intermediate energies. And our present lack of understanding of this process poses a serious obstacle to the effective use of such reactions as a tool for probing nuclear matter under extreme conditions.

Many different models have been formulated to study the nuclear disassembly process. They may be classified into two broad categories according to the time dependence of fragment formation. A considerable number of these models envision a simultaneous production of fragments. This is the case with the first discussion of the disassembly of nuclear matter by Randrup et al. [3]. Within this statistical picture, several multifragmentation models have been developed, particularly by Fai et al. [4], Bondorf et al. [5], and Gross et al. [6]. Simultaneous fragment formation is also assumed in the condensation model of Finn et al. [7] and the cold fragmentation picture of Aichelin et al. [8]. A contrasting picture is offered by models in which the fragments arise as a result of a succession of binary divisions of the initial excited nuclear system, or of the sufficiently excited products of such divisions. Among such models are the generalized evaporation model of Friedman and Lynch [9], the fission-evaporation description applied by Moretto et al. [10], and the sequential-binary decay model of López et al. [11].

It is instructive to recall that there are precedents for nuclear reaction mechanisms falling into one of these two categories. The emission of particles from the excited nuclei resulting from a fission process has been successfully described as a sequential decay process. The simultaneous production of complex fragments in a high-energy collision has been understood within the nuclear fireball model as resulting from coalescence of neighboring participant nucleons [12]. It is therefore not a priori obvious whether simultaneous or sequential processes will dominate nuclear disassembly at intermediate energies. In fact, the available inclusive data (e.g., the mass distribution of the fragments produced in the collision) can usually be reproduced about equally well by several different models. It is therefore imperative to identify more exclusive experimental information that would be more suitable for discriminating between the proposed models.

Botvina et al. [13] have calculated the number of massive fragments produced both using a multifragmentation and a pure evaporation model. They found that the evaporation calculations yielded a much smaller proportion of events in which several massive fragments are formed than multifragmentation. More recent fission-evaporation calculations of Moretto et al. [10] have agreed with the prediction of a rather small number of massive fragments. In the present work we explore the potential of the exclusive measurement of the massive-fragment multiplicity as a test to distinguish between two extreme reaction mechanisms, and use multifragmentation, sequential-binary and fission-evaporation models to simulate the decay of an excited nucleus for the purpose of comparing the different outcomes.

For the multifragmentation mechanism we use the model of Ref. [5] whose main ingredients are as follows: For a given mass and charge partition, it is assumed that
the fragments and nucleons coexist in a thermalized mixture within a prescribed volume. The excitation energies and entropies of the hot fragments are calculated with a liquid-drop model extended to finite temperatures. In forming the ensemble, all possible fragmentation channels are taken into account and their relative statistical weights are calculated from the total channel entropy. These initially hot primary fragments are then allowed to deexcite via light-particle evaporation, thus yielding the final fragments. In the present study we replace the breakup volume prescribed in the original reference [5] by the volume of a sphere circumscribing the two largest fragments, as this is more adequate for low multiplicities.

For the opposite extreme, sequential production of fragments, we consider two different approaches. One is the sequential-binary model of Ref. [11] in which the source is taken as a compound nucleus and is assumed to disassemble by sequential-binary decay. Thus, the initial binary split produces two new sources which may subsequently undergo further binary decay, provided that their excitation energy is high enough. Nucleon evaporation emerges as the most extreme mass-asymmetric split. This binary decay procedure is iterated until stability is reached. The resulting multifragment final state consists of individual nucleons and nuclear fragments. The fission widths for each of the possible splits are obtained on the basis of the simple Bohr-Wheeler transition-state treatment. For all possible binary channels, from symmetric fission to nucleon evaporation, the conditional barrier heights are calculated with a global parametrization developed by Świątecki [14].

As a second model for sequential production of fragments we employ the model of Charity et al. [15] in which a sequential-fission chain produces excited fragments that subsequently cool down by light-particle evaporation (i.e., first fission, then evaporation). Again the fission widths are obtained within the Bohr-Wheeler formula, but the conditional barriers are obtained either from a two-spheroid finite-range calculation [16] or from an extension of this calculation using more shape parameters, whereas the light-particle evaporation is treated by the Hauser-Feshbach theory. In order to achieve an informative comparison between the models, we assume that the angular momentum of the original decaying compound nucleus vanishes and that the charge of the fragments corresponds to β stability.

As an illustration, we consider the disassembly of an excited $^{150}$Gd nucleus and calculate the probabilities

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**FIG. 1.** Probabilities for observing 1, 2, 3, or 4 fragments with Z > 5 as functions of the initial excitation energy in the source $^{150}$Gd, calculated with the three different disassembly mechanisms considered: multifragmentation, sequential-binary, and fission-evaporation.

**FIG. 2.** The average multiplicity of fragments with Z > 5 and the associated standard deviation, as functions of the excitation energy in the source $^{150}$Gd, for the three mechanisms considered: multifragmentation (MF), sequential fission (SF), and fission-evaporation (FE).
$P(N)$ for producing $N$ massive fragments ($Z > 5$), as well as the first two moments of the multiplicity distribution, as functions of the excitation of the initial source. Figure 1 shows the variation of the probability $P(N)$, with $N = 1, 2, 3, 4$, for the three models considered. While the results differ from model to model, the multifragmentation and sequential-binary models give qualitatively similar results, whereas the fission-evaporation model never yields a substantial number of events with three or more massive fragments throughout the range of energies considered.

The average multiplicities $\langle N \rangle$ predicted by these models are shown in Fig. 2, together with the standard deviation $\sigma_N$ of the multiplicity distribution. They also exhibit different trends as functions of excitation energy. As noted above, the sequential-binary model predicts the highest multiplicity of massive fragments and this quantity increases considerably with energy. The multifragmentation results show a similar pattern. The fission-evaporation model, on the other hand, yields an almost constant and rather low average number of massive fragments. It may appear disturbing to find that conceptually similar models, namely, the sequential-binary and the fission-evaporation models, yield qualitatively different energy dependences for the multiplicity. This discrepancy may to a large degree result from the different methods used for calculating the barrier heights in the two models. It has already been noted that the barriers utilized in the fission-evaporation model are expected to be somewhat uncertain [10] and one should keep this in mind when using the model.

In conclusion, we have shown that two opposite disassembly scenarios, simultaneous multifragmentation and sequential-binary division, produce no significant differences for the energy dependence of the multiplicity of fragments with $Z > 5$. On the other hand, both of these differ from the fission-evaporation model which yields a very small number of such massive fragments, and consequently this scenario can probably be ruled out as the dominant decay mechanism responsible for events with high massive-fragment multiplicity. These findings suggest that the multiplicity of massive fragments does not provide a stringent test of the theoretical models of nuclear fragmentation.

*Note added.* After submitting this Brief Report we became aware of a recent study by Hubele *et al.* [17] which addresses the IMF production resulting from the fragmentation of 600 MeV/nucleon gold projectiles. This study calculates the dependence of the IMF multiplicity on the quantity $Z_{\text{bound}}$ using the statistical models of Refs. [5,6] as well as the fission-evaporation model of Ref. [15]. It is found that the fission-evaporation model is unable to reproduce the IMF data (whereas the two statistical models do considerably better). Our present study corroborates this failure, but also demonstrates that the sequential-binary model of Ref. [11] yields results that are rather similar to those resulting from a simultaneous statistical disassembly. It would therefore be interesting to extend the study of Ref. [17] to the model of Ref. [11], particularly if one seeks to infer the basic character of the process from such studies.

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