RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 44, NUMBER 2 AUGUST 1991

Multifragmentation for $^{36}Ar + ^{238}U$ treated as statistical dynamic interaction processes

M. Blann and M. G. Mustafa
Lawrence Livermore National Laboratory, Livermore, California 94550
(Received 5 April 1991)

The exclusive multifragment multiplicities for the system $^{36}Ar + ^{238}U$ at 35 MeV/nucleon incident energy are calculated using the Boltzmann master equation for the fast cascade, and the Weisskopf-Ewing evaporation model for successive binary decay of the equilibrated residues. These calculated results are consistent with the experimental results of Kim *et al.* We show that the multiplicity distribution in such a model has a sensitivity to the equilibrated excitation, so that multiplicity could be an observable characteristic of excitation. This in turn may be used to infer time delay for fragment emission (in a model dependent way).

Excitation of nuclei to high energies involves first a dynamic, fast process, followed by statistical deexcitation of residues surviving the fast processes. Interpretation of experimental results requires an understanding at the theoretical level of the relative importance and interplay of the slower statistical and fast dynamical interactions.

Kim *et al.* [1] reported multifragment emission measurements for the reactions of 35 MeV/nucleon ^{36}Ar on ^{238}U. We will use these data to test an interpretation based on a combined dynamic plus statistical description of heavy-ion reactions. Our tools will be the Boltzmann master equation (BME), which was successfully used to predict heavy-ion precompound decay prior to experimental observation [2], and an appropriate modification of the Weisskopf-Ewing (WE) evaporation theory [3,4]. We use the BME to predict the average mass, charge, and excitation of the residue following the fusion/precompound decay phase, then assume sequential binary decay processes for equilibrated residues. The partition of excitation between heavy residues and light fragments is explicitly calculated, as is the decay of the excited light fragments to particle-bound products. From comparisons of these results with experimental yields, we will see the degree to which the experimental results may be interpreted by such a statistical-dynamic approach, and investigate the sensitivity of the data to the excitation energies of the equilibrated nuclear species.

The use of the BME in treating precompound decay in heavy-ion reactions, and in estimating the equilibrated excitation has been adequately discussed in the literature; we refer to these papers for details of the present calculations [5]. The BME has been shown to give an excellent agreement with experimental high-energy neutron and proton emission spectra, without parameter variation. However, precompound decay also includes nucleons with energies which are similar to those emitted from equilibrated systems; the differentiation at these emitted neutron energies is ambiguous [6]. Therefore, estimates of the energy removed in precompound processes has, at present, a subjective aspect. We will use a value based on the excitation when the obvious fast emission processes have ceased, bearing in mind that complete thermalization may come at a somewhat later time, and therefore at lower internal excitation.

In Fig. 1 we show the BME results for excitation versus time for the residue formed when 35 MeV/nucleon ^{36}Ar is incident on ^{238}U. The calculation is performed for time increments of 2×10^{-23} sec. At the extreme left, we see the excitation resulting from the first nucleon interactions during the coalescence (fusion) process. The BME calculates the energy loss due to the emission of nucleons as well as the excitation brought in by the coalescing nuclei. Fusion is complete (in the constant velocity assumption used) at $\approx 1.4\times10^{-22}$ sec; the maximum excitation (800 MeV) occurs at 1.2×10^{-22} sec. If a compound nucleus had been instantly formed, the internal excitation ($E_{c.m.} + Q$) would have been 970 MeV; this value is indicated by the horizontal line in Fig. 1. The difference in these energies illustrates the point that the full excitation is *never* available due to the dynamical nature of the formation and relaxation processes.

Subjective analyses of the time derivatives of the calcu-

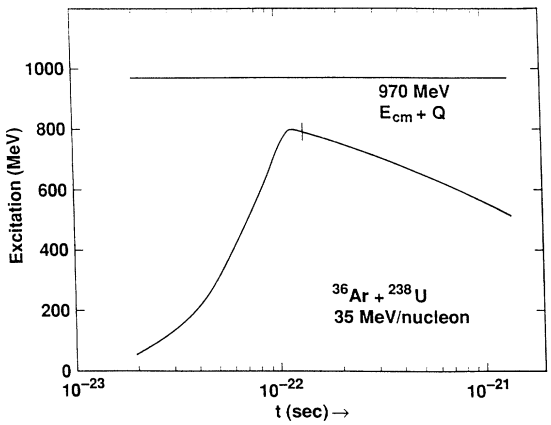

FIG. 1. Excitation vs time for the reaction $^{36}Ar + ^{238}U$ at 35 MeV/nucleon as calculated with the Boltzmann master equation. The reaction begins at 2×10^{-23} sec (the time step used in the calculation). The excitation is shown on the ordinate, time on the abscissa. Fusion is complete at 1.4×10^{-22} sec, indicated on the excitation vs time curve by a short horizontal line slightly beyond the maximum excitation. The horizontal line at 970 MeV represents the excitation available in the center of mass (i.e., if a compound nucleus were instantaneously formed).

lated neutron emission rates leads to an estimate of equilibration after $\approx 3\times10^{-22}$ sec, at which time the internal excitation is ≈ 720 MeV, and on average nine neutrons and two protons have been emitted. We initially use this estimate to give the starting point for the statistical emission process.

An inference from some experiments is that the collective fission process may have time delays of 10^{-20}–10^{-19} sec [7]. Perhaps, then, should heavy-fragment emission also be delayed with respect to nucleon emission by a period less than that for fission? This is an interesting open question. We will consider the residual nucleus at 10^{-21} sec (at which time the internal excitation is ≈ 550 MeV) to illustrate the sensitivity of calculated multifragmentation yields to the initial excitation of the equilibrated nucleus; the excitation may be seen (Fig. 1) to be related to any time delay for fragment decay since the residual postfusion excitation energy decreases monotonically with time.

Two new codes were derived from the WE-type ALICE nuclear reactions code [4,8]. The first permitted the emission of up to 20 ejectiles in addition to n, p, and α particles, with explicit folding over all possible energy partitions between light and heavy fragments for fragments of $A > 4$. Additionally, the exclusive multiplicity of emitted fragments may be followed. The second code version accepts the excited fragments up to $Z=20$, $A=48$ from the first code and follows the deexcitation of these fragments to particle-bound residues. Greater detail on these codes may be found elsewhere [4,8].

Our goal at present is to investigate whether or not such a statistical-dynamic approach provides a satisfactory interpretation of the data, and if so, the sensitivity of the results to the excitation (temperature) of the equilibrated system. We have not attempted to use all the "best possible" components in our calculations; to do so would delay results for a very long period. We have used a Fermi-gas level density, without fitting to known low-lying levels of light ejectiles. We do, however, extrapolate the single-particle level-density parameter based on the work of Toké-Swiatecki to allow for surface effects [9]. Limits on level densities due to restrictions to bound nucleon levels should also be considered [10,11], but are not incorporated in the present work. The parabolic barrier model of the ALICE code was used to generate inverse cross sections for clusters; the parameters of this routine had been selected to give a reasonable reproduction of experimentally measured heavy-ion fusion excitation functions (the optical model was used for neutron and proton inverse cross sections) [12,13]. A more precise calculation would result from using a very careful empirical parametrization of the experimental fusion excitation function data, with particular attention to the near and subbarrier regions [13] which are very important to the evaporation process.

Preliminary calculations were performed for 60 light cluster ejectiles; the 20 most abundant isotopes were selected for use in the calculations to be presented. These are compared with experimental measurements of Kim *et al.* in Fig. 2. The ejectiles teated were ^{9}Be, ^{10}Be, ^{11}B, ^{12}C, ^{14}C, ^{15}N, ^{16}O, ^{18}O, ^{21}F, ^{22}Ne, ^{23}Ne, ^{27}Mg, ^{28}Mg, ^{28}Mg, ^{30}Si, ^{31}Si, ^{32}Si, ^{36}S, ^{37}S, ^{42}Ar, and ^{43}Ar.

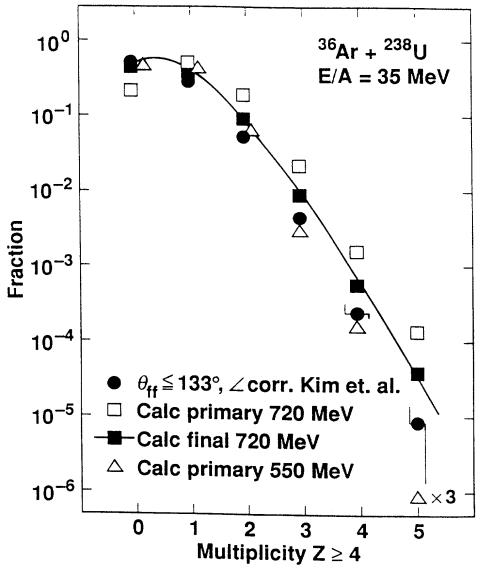

FIG. 2. Calculated and measured multiplicities for the $^{36}Ar+^{238}U$ system. The ordinate gives the fraction of reactions for which zero to five fragments of $Z \geq 4$ were observed. In the case of experimental data, the measurements were gated on fission fragments with an opening angle $\leq 133°$. There is no such gate on calculated results. The experimental data of Kim *et al.* were adjusted to 4π solid angle as described in the text. The open squares represent calculated primary yield results for 720 MeV of excitation; the solid squares joined by a smooth curve are the results for bound final fragments. The open triangles represent calculated primary yields when the initial excitation is assumed to be 550 MeV.

The MSU [1] group made measurements of multifragmentation with several "gates." In Fig. 2 we show the experimental results for multiplicities which were gated on fission fragments at an angle of 133°, i.e., reasonably central collisions. The solid angle was reported as $\approx 80\%$ of 4π; additionally, there were kinematic cutoffs for the detectors. We have taken the liberty of adjusting the data reported by Kim *et al.*, by $1/(0.80)^m$, where m is multiplicity (reported for fragments of $Z \geq 4$) as a solid angle correction. This is a very crude approximation; the fragment emission is not isotropic in the laboratory frame, but is kinetically focused forward. Neither is the missing detector solid angle isotropically distributed (see Ref. [1] for details). Nonetheless we make this correction as a reasonable estimate; the change from the uncorrected data is 20% at multiplicity 1, and 67% at multiplicity 5, which is down five orders of magnitude. The complicated relationships of experimental kinematic cutoffs and problems of elemental resolution makes it difficult to be more precise. There is no correction for the counter kinematic cutoffs, so data points corrected for cutoffs would lie higher than those shown in Fig. 2. This correction should be greater the higher the multiplicity, since the fragment kinetic energies will decrease with increasing multiplicity. This means an increasing fraction of the ejectile spectrum would lie below the low-energy detector cutoffs. The experimental data of Fig. 2, therefore, represent lower lim-

its.

We assume the nucleus $^{263}_{108}X$ equilibrated, following the fast cascade, with ≈ 720 MeV of excitation. The primary emission multiplicities (before the excited clusters undergo further multiple binary decay) are shown in Fig. 2, by the open squares. They underestimate the zero multiplicity yield, and overestimate all others. However, the experiment measures the final particle bound clusters. Calculated bound cluster multiplicities are shown by solid squares, which for clarity have been joined by a smooth line; these results are in reasonable agreement with the experimental data, which are lower limits.

The sensitivity of the calculation to excitation energy may be illustrated by assuming that cluster emission is delayed until 10^{-21} sec after initiation of the reaction (this being a completely arbitrary time). At this time, the average nucleus is $^{263}_{108}X$ at 550 MeV of excitation. For this case we show only the multiplicities of the primary fragments (triangles) before post emission deexcitation. These results are in reasonable agreement with experimental data for multiplicities up to 2; beyond that they underestimate the data, remembering that the data points will increase due to kinematic cutoffs, while the calculated values will decrease due to further binary deexcitation. In particular we note that the calculated result for multiplicity 5 is quite low. This discrepancy will increase when the corrections to data and calculated results have been made. This illustrates that the exclusive multiplicity measurements are sensitive to the excitation of the equilibrated nucleus, to the extent that the assumed mechanism is valid.

In Fig. 3 we show some detail of the calculation of the deexcitation of primary fragments. The fractional yields for the first ejectiles from $^{263}_{108}X$ are shown as solid circles, summed over mass number for each atomic number considered. The histogram represents the calculated particle-bound yields. It is clear from Fig. 3 that most clusters observed under similar circumstances result from the sequential decay of a heavier cluster. Therefore, the high-energy region of the cluster spectrum is not likely to yield information on the temperature of the emitting nucleus, nor is the low-energy region likely to be indicative of the Coulomb barrier of the parent. These comments are based on the considerable "kinematic kick" which the light ejectiles receive during the deexcitation process.

We have provided one possible interpretation of the exclusive multiplicity measurements of Kim *et al.* as a fast dynamic reaction during which $\approx 25\%$ of the excitation is removed by precompound neutron and proton emission, followed by the heavy residue deexciting by successive equilibrium binary decay. For this calculation, it was important to consider the partition of available excitation between heavy and light fragments, and the binary decay of the primary ejectiles to give bound clusters as are observed in experimental measurement. The agreement is over five order of magnitude, with no attempt having been made to adjust parameters in the calculation.

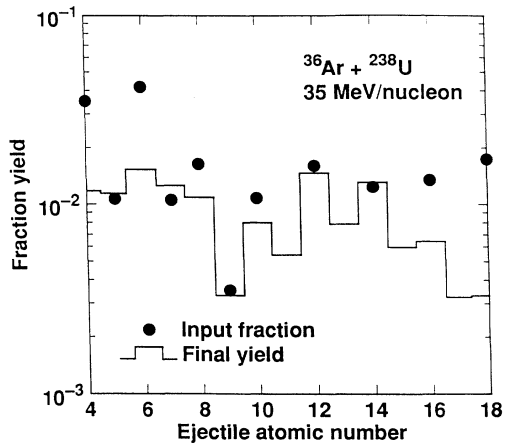

FIG. 3. Initial and final yields for primary fragments emitted from a compound nucleus at 720 MeV. The solid circles represent the primary fractional yields for the first ejectiles (multiplicity one or more). The histogram represents the yields after the ejectiles have deexcited to particle-bound nuclei.

Comparisons of calculations each with the same approximations (level densities, inverse cross sections) at two different initial excitation energies, shows that the exclusive multiplicity measurement is sensitive to excitation energy of the equilibrated nucleus. More quantitative deduction of the excitation will require better input into the model calculations, and experiments performed with detectors having low kinematic cutoffs for cluster detection, and near 4π acceptance angles. The interpretation we have presented is perhaps the simplest possible in terms of previously investigated reaction mechanisms. It will be interesting to see which alternative mechanisms [14] will provide equally good interpretations of data of the type considered, and then to see what experimental measurements might be used to select the better models to pursue in each regime of target-projectile mass and energy.

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

[1] Y. D. Kim *et al.*, Phys. Rev. Lett. **63**, 494 (1989).

[2] M. Blann, in *Proceedings of the International School Nuclear Physics, Bucharest, 1974,* edited by A. Ciocanel (Editura Academiei Republicii Socialiste Romania, Bucharest, Romania, 1976), p. 249; M. Blann, A. Mignerey, and W. Scobel, Nukleonika **21**, 335 (1976); M. Blann, Phys. Rev. C **23**, 205 (1981); M. Blann, Nucl. Phys. A **235**, 211 (1974).

[3] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 471 (1940).

[4] M. Blann, M. G. Mustafa, G. Peilert, H. Stöcker, and W. Greiner, Phys. Rev. C **44**, 431 (1991).

[5] M. Blann, Phys. Rev. Lett. **54**, 2215 (1985); M. Blann, Phys. Rev. C **32**, 1231 (1985); B. A. Remington, M.

Blann, and G. F. Bertsch, Phys. Rev. Lett. **57**, 2909 (1986); Phys. Rev. C **35**, 1720 (1987); B. A. Remington and M. Blann, *ibid.* **36**, 1387 (1987); M. Blann, in *The Nuclear Equation of State, Part A,* edited by W. Greiner and H. Stöcker, NATO Advanced Study Institutes Ser. B Vol. 216A (Plenum, New York, 1989), p. 341.

[6] M. Blann, Phys. Rev. C **37**, 2231 (1987).

[7] D. J. Hinde, Nucl. Phys. A **452**, 550 (1986); J. O. Newton *et al.*, Phys. Rev. C **37**, 2923 (1988); D. J. Hinde *et al.*, *ibid.* **39**, 2268 (1989); D. J. Hinde, D. Hilscher, and H. Rossner, in *Proceedings of the International Conference on Fifty Years Research in Nuclear Fission, Berlin, 1989* [Nucl. Phys. A **502**, 497c (1989)]; in *Proceedings of the Symposium on Nuclear Dynamics and Disassembly, Dallas, TX, 1989,* edited by J. Natowitz (World Scientific, Singapore, 1989), p. 289; H. Rossner, D. Hilscher, D. J. Hinde, B. Gebauer, M. Lehmann, M. Wilpert, W. Scobel, and E. Mordhorst, Phys. Rev. C **40**, 2629 (1989).

[8] M. Blann and J. Bisplinghoff, Report No. UCID-19614, 1982 (unpublished); M. Blann and W. Scobel, Report No. UCID-20169, 1984 (unpublished); M. Blann and H. K. Vonach, Phys. Rev. C **28**, 1648 (1983).

[9] J. Toké and W. J. Swiatecki, Nucl. Phys. A **372**, 141 (1982).

[10] S. M. Grimes (private communication).

[11] A. V. Ignatyuk (private communication).

[12] M. Blann, in *Proceedings of the International Conference on Nuclear Physics, Munich, 1973,* edited by J. DeBoer and H. J. Mang (North-Holland, Amsterdam, 1973), Vol. 2, p. 657.

[13] W. Scobel, A. Mignerey, M. Blann, and H. H. Gutbrod, Phys. Rev. C **11**, 1701 (1975).

[14] D. H. Boal and J. N. Glosli, Phys. Rev. C **37**, 91 (1988); W. Bauer *et al.*, Phys. Rev. Lett. **58**, 863 (1987); K. Sneppen *et al.*, Nucl. Phys. A **480**, 342 (1988); J. Aichelin *et al.*, *ibid.* **488**, 437c (1988); T. J. Schlagel and V. R. Pandharipande, Phys. Rev. C **36**, 162 (1987); C. Hartknack, H. Stöcker, and W. Greiner, in *The Nuclear Equation of State,* edited by W. Greiner and H. Stöcker, NATO Advanced Study Institutes Ser. B Vol. 216A (Plenum, New York, 1989), Part A, p. 239; G. Peilert *et al.*, *ibid.*, p. 283; J. Randrup, *ibid.*, p. 401; A. Adorno, M. Colonna, M. Di'Toro, and G. Russo, *ibid.*, p. 413.